Smart Solutions to Manage Peak Electricity Demand in Saudi Arabia

By

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Abstract

Electricity consumption in the Kingdom of Saudi Arabia (KSA) grew at an annual rate of about 7% in the last two decades as a result of population and economic growth. The consumption of the residential sector accounts for over 50% of the total energy generation. Moreover, the energy consumption of air conditioning (AC) systems reaches up to 70% of the total electricity consumption of residential buildings in the summer months, leading to a situation where peak electricity demand occurs in early afternoon and lasts for about five hours. This thesis aims to tackle this challenge, using renewable energy technologies and smart grid management options. It proposes promising and practical solutions for mitigating the electricity peak demand of the residential sector that will conform to national strategies and policies.

Firstly, the deployment of PV panels, whose slope and orientation are optimized with respect to the shape and timing of the energy demand profile so that the time that the maximum amount of energy is produced by the solar systems matches the time when energy demand is at its peak, is proposed. The optimization of the slope and orientation also takes into account the reduction in the performance of solar PV systems due to the accumulation of dust. Numerical results are presented for PV panels installed on government buildings – particularly on the roofs of schools, malls and mosques in residential neighbourhoods – in the city of Riyadh in KSA. Secondly, to reduce the energy consumption due to AC in the residential sector, the use of smart control of thermostat settings, via (i) scheduling and advance control of the operation of AC systems, and (ii) remotely setting the thermostats appropriately by the utilities, is proposed. Crucially, to gain an understanding of the short-term and the long-term occupancy behaviour for residential buildings, a survey is carried out to investigate some of the behavioural factors causing high energy consumption and the insights gained enabled the development of the proposed practical approaches so that the comfort of occupants is not compromised. Thirdly, the use of solar water heating (SWH) systems for the supply of domestic hot water is proposed. A study on the reduction in peak electricity demand achievable when domestic hot water is supplied using SWH systems is presented.

KSA has high potential for developing electricty generation via PV solar and SWH systems and for reducing energy consumption of AC systems in residential sector, and this study includes new insights on achievable energy production and savings should these technologies be adopted on a large scale in KSA.

List of Publication

The following papers have been published as a result of this research:

J. Alshahrani and P. Boait, “Smart demand-side and supply-side solutions to manage peak electricity demand from the residential sector of Saudi Arabia”, The 1st Faculty of Technology PGR Students Conference, De Montfort University / 8 June 2016 **(poster)**.

J. Alshahrani and P. Boait, “Smart demand-side and supply-side solutions to manage peak electricity demand from the residential sector of Saudi Arabia”, 4th LoLo Conference, Energy in an Age of Uncertainty, Loughborough University / 13 June 2017 **(poster)**.

J. Alshahrani and P. Boait, “Finding the Optimum Orientation for PV Systems Matched to the Timing of the Demand Profile”, 5th International renewable and Sustainable Energy Conference IRSEC17, Tangier-Morocco / 4-7 December 2017 **(paper)**.

J. Alshahrani and P. Boait, “Finding the Optimum Orientation for PV Systems Matched to the Timing of the Demand Profile”, 2017 International Renewable and Sustainable Energy Conference (IRSEC), Tangier, 2017, pp. 1-6. doi: 10.1109/IRSEC.2017.8477358 **(paper)**.

J. Alshahrani and P. Boait, “Deployment of Photovoltaic Systems in Public Buildings of Saudi Arabia including the Effects of Dust Accumulation”, 35th EU PVSEC 2018 in Brussels 24 - 28 September **(paper)**.

J. Alshahrani and P. Boait, “Reducing High Energy Demand Associated with Air-conditioning Needs in Saudi Arabia”, Energies, energies-389527, 28-12-2018 **(paper)**.

J. Alshahrani and P. Boait, “Deployment of Photovoltaic Systems in Public Buildings of Saudi Arabia including the Effects of Dust Accumulation”, ASTES Journal, **(paper under revision)**.

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List of Abbreviations and Nomenclature

Notation	*Description*
AC	Air Conditioning System
CPP	Critical-Peak Price
DLR	Direct Load Control
DR	Demand Response
DSM	Demand Side Management
ECM	Energy Conservation Measures
ECRA	Electricity and Co-Generation Regulatory Agency
EER	Energy Efficiency Ratio
GCC	Gulf Cooperation Council
GW	Gigawatt
HAN	Home Area Network
HVAC	Heating, Ventilation, and Air Conditioning
I&C	Interruptible and Curtailable Load
ICT	Information and Communication Technology
IEA	International Energy Agency
IoT	Internet of Things
KACARE	King Abdullah City for Atomic and Renewable Energy
KSA	The Kingdom of Saudi Arabia
MC	Master Controller
MOWE	Ministry of Water and Electricity
MW	Megawatt
NAN	Neighbourhood Area Network
NEEP	National Energy Efficiency Program
PV	Solar Photovoltaic System
RTP	Real-time Price
SBC	Saudi Building Code
SEC	Saudi Electricity Company
SEEC	Saudi Energy Efficiency Centre
SR	Saudi Riyal
SWH	Solar Water Heating
ToU	Time-Of-Use
U-value	Measure of Material Effectiveness as an Insulator
UAE	United Arab Emirates
UK	United Kingdom
US	United States

USD	United States Dollar
WAN	Wide Area Network
$\boldsymbol{\omega_i}$	Solar hour angle of the ith hour (the time before solar noon expressed as negative degrees ($-\omega_i$), and the time after solar noon expressed as positive degree (ω_i) and ω_i equals 0° at solar noon)
$\boldsymbol{\omega_s}$	Solar hour angle for sunset (and $-\omega_s$ for sunrise)
$\boldsymbol{\alpha}$	Solar elevation angle
$\boldsymbol{\beta}$	PV panel tilt (elevation) angle from the horizontal
$\boldsymbol{\delta}$	Solar declination angle
$\boldsymbol{\eta}$	Inverter efficiency (in percentage, %)
$\boldsymbol{\theta}$	Solar Zenith angle (angle between the sun and a line vertical to the surface of the Earth)
$\boldsymbol{\varphi}$	Latitude of the location of a PV system
$\boldsymbol{e_c}$	Empirical constant (e_c= 0.65 if φ > 45° or e_c= 0.75 if $\varphi \leq$ 45°)
$\boldsymbol{r_b}$	Panel angle incident beam radiation factor
$\boldsymbol{r_d}$	Panel angle incident diffuse radiation factor
$\boldsymbol{s_h}$	Angle between solar hour angle of sunrise and solar hour angle of sunset for a given day
$\boldsymbol{d}$	Sky's clearness factor for a given day
$\boldsymbol{n}$	Day number in a year (where $n = 1$ on the 1st January)
$\boldsymbol{s}$	Number of sunshine hours for a given day
$\boldsymbol{E_T}$	Total energy generated by a solar PV plant on a given day
$\boldsymbol{H_o}$	Extra-terrestrial energy directed to a unit horizontal area over a given day and a given geographic location
$\boldsymbol{B}$	Solar beam energy on a unit horizontal area over a given day and location
$\boldsymbol{D}$	Solar diffuse energy on a unit horizontal area over a given day and location
$\boldsymbol{G}$	The total solar energy on unit solar panel area over a given day and location and for a given panel angle of elevation
$\boldsymbol{K}$	Clearness index for a given day
$\boldsymbol{S}$	Solar radiation power constant, 1.367 kW/m^2
$\boldsymbol{X}$	Solar PV plant electricity generation capacity

Chapter 1: General Introduction

1.1 Introduction

The electricity sector in the Kingdom of Saudi Arabia (KSA) is faced with great challenges in meeting the increasing electricity demand that is a fundamental requirement for social and economic growth. The fast growth in energy consumption in the kingdom over the last two decades, which has never dipped below 6% per year, has been driven largely by the increasing electricity demand in the residential sector due to population growth. The residential sector consumes over 50% of KSA’s total electricity production – the remaining 50% being split among industry, commercial sector and governmental agencies. Figure 1.1 illustrates the distribution of electricity consumption by sector in 2014.

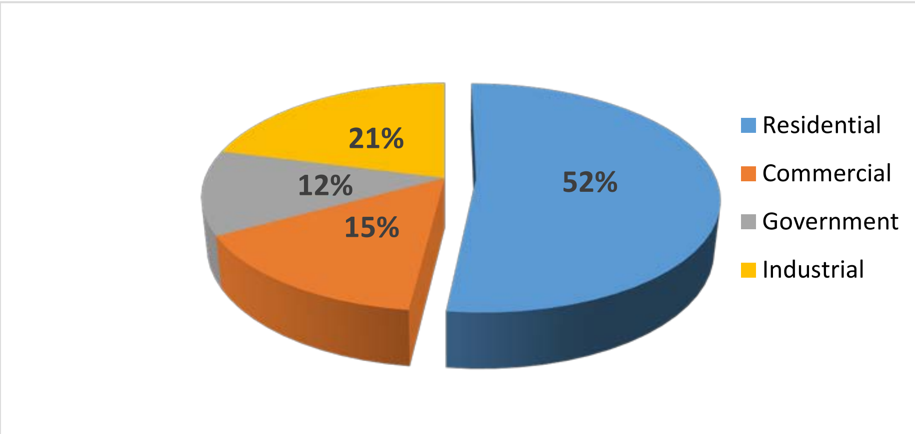


Figure 1.1: Electricity consumption by sector in KSA (ECRA, 2014)

In KSA, during the summer, 60% to 70% of the energy consumed by residential buildings is due to the air-conditioning systems (ECRA, 2014; Alrashed & Asif, 2014). The need for air-conditioning systems in the buildings is due to the low quantity of rainfall and the high temperature during the daytime in the country which is similar to other countries with desert-like climates. The average summer temperature in KSA can reach up to 45 ^{o}C – typically, the temperature rises soon after daybreak and remains high until sunset. Figures 1.2 and Figure 1.3 show the typical daily electricity load curve of KSA during summer and winter, respectively, which are created by calculating a load curve using average values of load over time intervals (ECRA, 2015). As can be observed in Figure 1.2, the peak demand for electric power in KSA occurs during midday between 12:00 and 17:00 in summer (from May to September) – the surge in that period of the day in summer is non-existent in the winter. Comparing the two figures further, for example, the demands at 13:00 in the summer and winter during the weekdays are 52 GW and 26.5 GW, respectively, and during the weekend 56 GW and 28 GW, respectively. The surge in demand at midday during summer is mainly attributed to the loads required by air conditioning systems for cooling (Almutairi *et al.*, 2015). From the figures, it can also be noticed that AC are used day and night during the summer (at 19:00 in the night on the weekday, the demands are 51 GW and 30 GW in summer and winter, respectively). In KSA, electricity demand is continuing to outpace growth in supply in recent times, prompting the Saudi Electricity Company (SEC) to limit electricity for some areas during peak demand times. Moreover, SEC is also requesting some large customers to turn off their supply from the grid at certain times and to put their emergency generators in operation in order to reduce the grid-supplied load during the summer peak period (Hagihara, 2013).

In addition, with the aim of meeting the peak demand, the construction of additional power plant or improvements on existing ones is required. Due to the increase in energy demand as a result of growth in the number of residential buildings and more industrial customers being connected to the grid, old power plants are being expanded and new facilities are being built (Obaid & Mufti, 2008). In fact, additional generation capacity of 2 to 5 GW is added each year to meet the country's growing electricity demand (ECRA, 2015) as the current committed capacity will not be sufficient to meet the projected demand according to King Abdullah City for Atomic and Renewable Energy (KACARE).

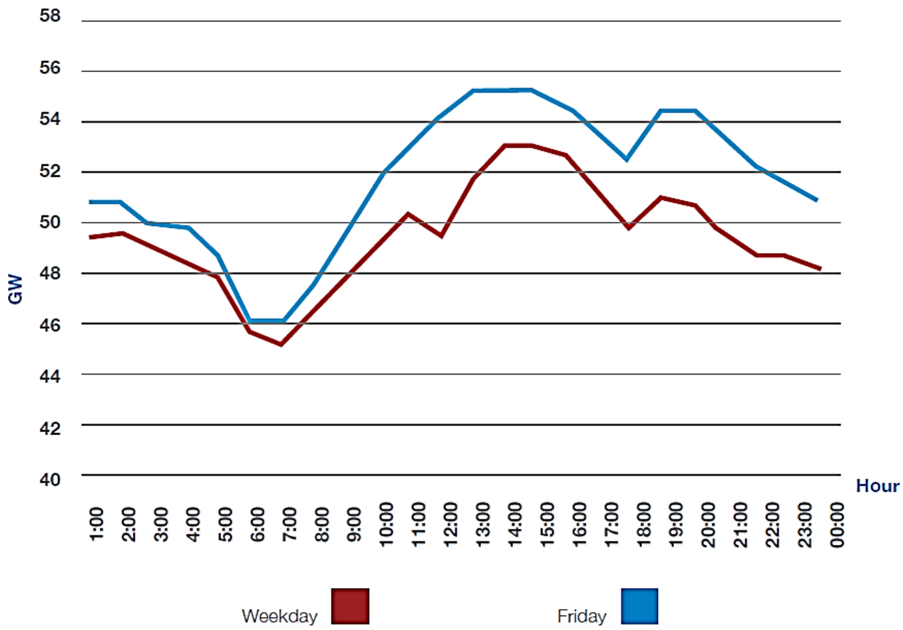


Figure 1.2: Typical daily electricity load curve of KSA during summer (ECRA, 2015).

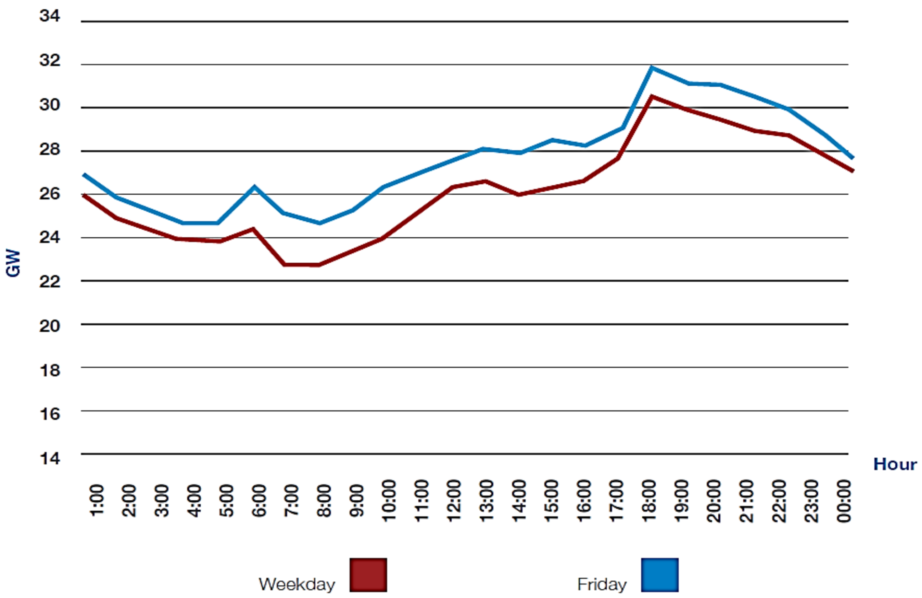


Figure 1.3: Typical daily electricity load curve of KSA during winter (ECRA, 2015)

This thesis will therefore proffer some practical solutions to manage the peak electricity demand of the residential sector that conform to the current national strategies and policies. The remainder of this chapter is arranged as follows: The geographic location, population, growth, and climate of KSA are described in Section 1.2. The growth of the electricity market, trends on the electricity generation capacity and peak load, and the prediction of future energy needs of KSA are presented Section 1.3. Section 1.4 describes KSA's electricity generation and consumption in terms of its importance to the nation's GDP and in comparison, with other countries. The current government policy in terms of energy resources, generation, conservation and management as well as the motivation for the current policy are presented in Section 1.5. As KSA is moving towards the exploitation of renewable energy resources and has recognised the need to manage the growth in peak demand, Section 1.6 describes the overall objectives of this thesis from that perspective. Section 1.7 outlines the structure of this thesis report.

1.2 Profile of the Kingdom of Saudi Arabia

The KSA lies between the latitude of 16.38 °N and 32.15 °N and the longitude of 34.57 °E and 55.66 °E; refer to Figure 1.4. It is the largest country in the Middle East with a total surface area of approximately 2.15 million square kilometres – that is, roughly half the size of the European Union. According to KSA's Central Department of Statistics and Information, there has been a dramatic growth in the total population of Saudi Arabia from 16,361,453 in 1990 to 31,540,372 in 2015 – an average annual growth of 2.5%. Moreover, the population is expected to reach 37,610,985 by 2025 (General Authority for Statistics Kingdom of Saudi Arabia, 2017).

KSA has a desert climate which is characterized by high heat during the day and a temperature drop at night; the heat becomes high shortly after sunrise and stays so until sunset. In a year, there are mainly two seasons: winter and summer. The average temperature is about 45° C in the summer, but the ambient air temperatures could reach up to 50° C (STO-Website, 2018).

Figure 1.4: Saudi Arabia Location

1.3 Electricity Market in KSA

The electricity market in KSA has grown rapidly by about 7% annually over the past 20 years. The peak demand of electricity in the summer has increased by 121% between 2004 and 2016 (that is, from 28 GW in 2004 to about 62 GW in 2015. This growth is expected to continue annually by at least 6% (ECRA, 2014; Nachet & Aoun, 2015). This growth is largely driven by population growth, a high demand for air conditioning (AC) during the summer months, and low electricity tariffs which is one of the lowest in the word (refer to Figure 1.6 for comparison with other countries). The electric generating capacity of KSA as of 2016 is 66 GW and it plans to increase this capacity to 120 GW by 2032 (KACARE, 2018). Figure 1.5 shows the electricity generation capacity and peak load in KSA from 2007 to 2015.

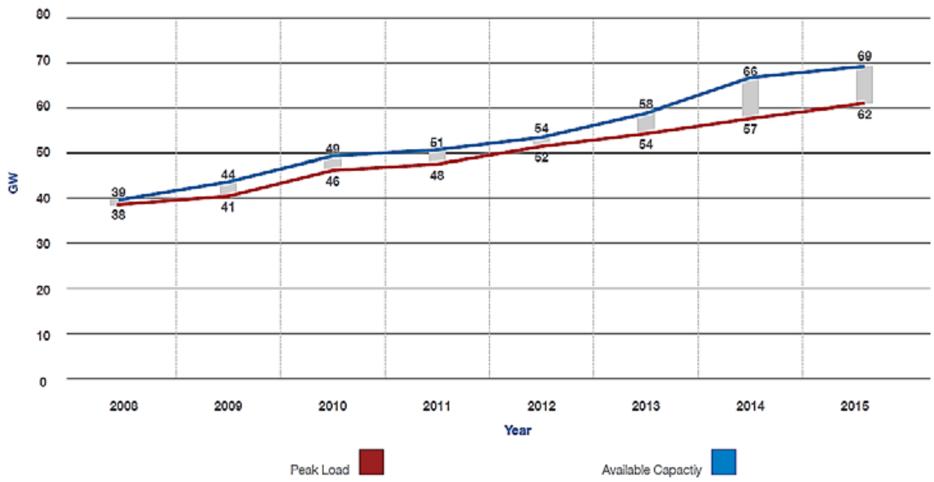


Figure 1.5: Electricity generation capacity and peak load in KSA (ECRA, 2015)

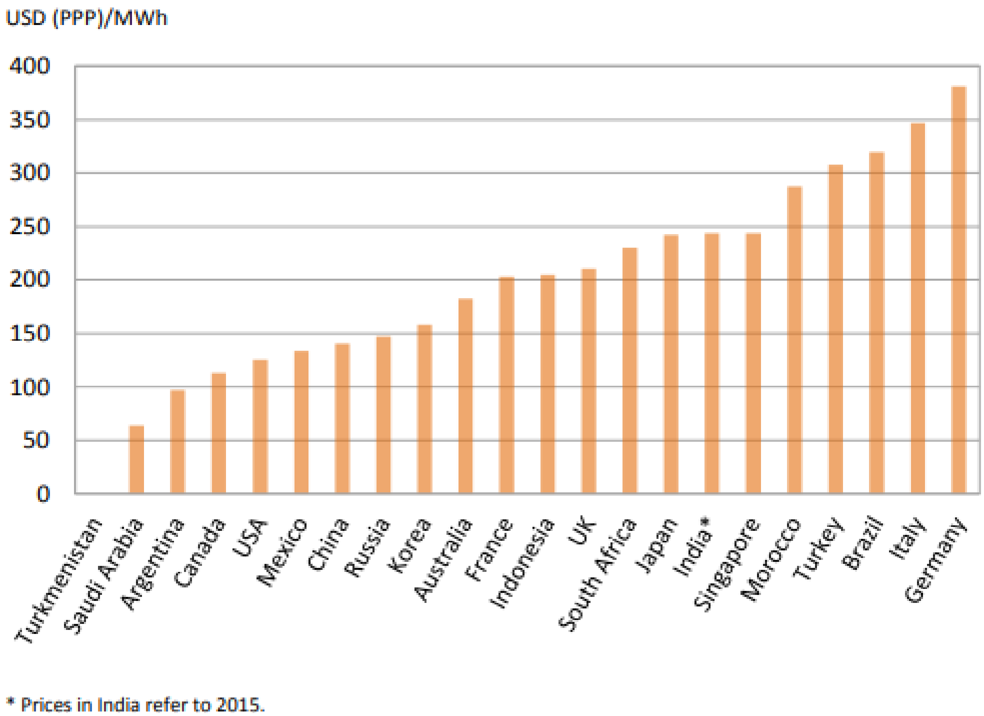
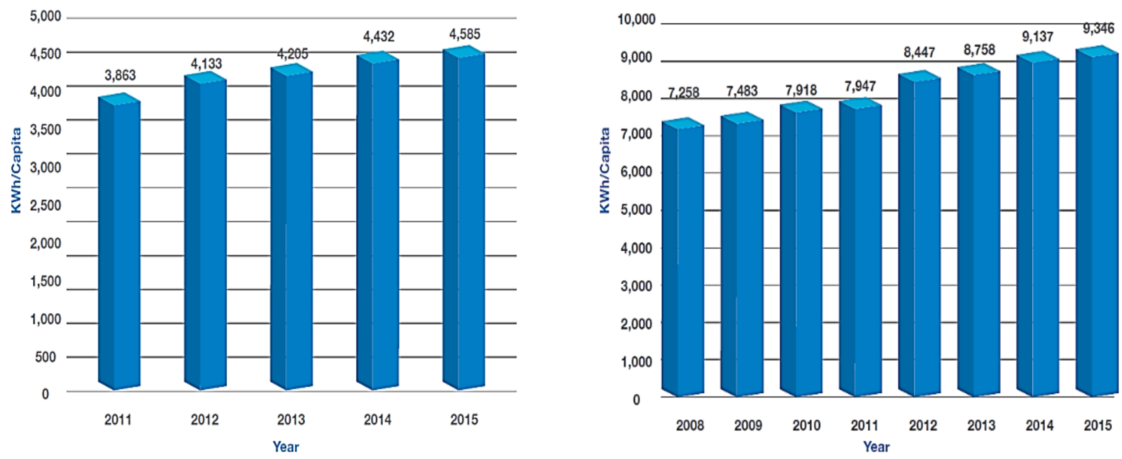


Figure 1.6: Residential electricity prices in selected economies, PPP adjusted – 2016 (IEA, 2018)

Among the Gulf Cooperation Council (GCC) states, KSA has the largest and fastest growing building construction sector. According to estimates, 2.32 million new houses will be built by 2020 so as to meet the demand of the increasing population. The residential sector has contributed significantly to the power consumption in KSA due to the increased demand for cooling. In particular, up to 70% of the electricity sold is attributed to the electricity consumption of air conditioning systems in residential buildings (ECRA, 2014). Thus, the hot climate in the region and the corresponding operation of air conditioning systems explains, to a large degree, the high levels of energy consumption (Taleb & Sharples, 2011).

1.3.1 Per Capita Energy Consumption

KSA has one of the highest per capita energy consumption rates in the world. The consumption has increased from 7,019 kWh/capita in 2007 to 9,137 kWh/capita in 2015 as shown in Figure 1.7. This is almost three times more than the world's average (ECRA, 2014); for comparison, in 2014, the per capita energy consumption of the four largest Arab countries in terms of population, namely, Algeria, Egypt, Morocco, and Sudan are 1356 kWh/capita, 1658 kWh/capita, 901 kWh/capita and 190 kWh/capita, respectively.



(a) (b)

Figure 1.7: Annual per capita energy consumption in KSA: (a) Residential sector, and (b) all sectors (ECRA, 2015)

1.3.2 Domestic Pricing of Electricity

Electricity and saltwater desalination and subsidies cost KSA approximately US$ 33 billion per year. In particular, within the last twenty years until the end of 2015, price changes on the cost of electricity have been relatively fixed; the cost of electricity, which was 0.08 US$/kWh (0.30 SAR/kWh) in 1974, was reduced to 0.04 US$/kWh (0.15 SAR/kW h) in 1984. By 2011, separate prices for different sectors were introduced but the cost was further reduced to 0.03 US$/kWh (0.12 SAR/kW h) for residential customers all year long. The industrial time-of-use (ToU) rates, however, oscillate around 0.14 US$ (approximately between 0.14 SAR/kWh and 0.15 SAR/kWh) (Groissböck & Pickl, 2016). Prior to 1st January 2018, the distribution of bills per level of monthly consumption for the residential sector is given Figure 1.8. Table 1.1: The current electricity tariff in KSA (SR/kWh) shows the current prices of electricity for different sectors in KSA (SEC, 2015).

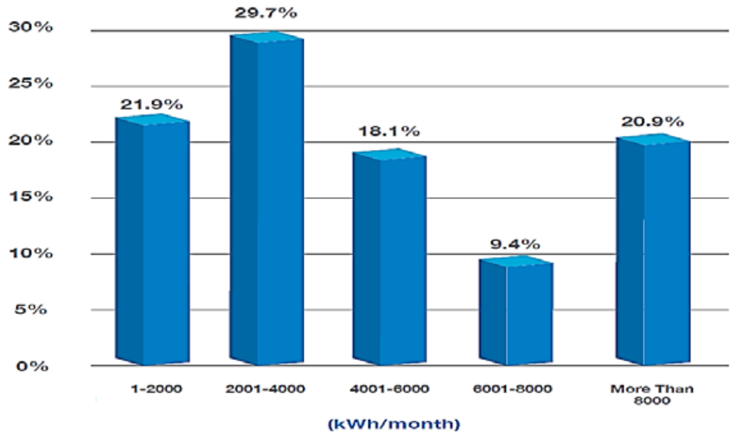


Figure 1.8: The distribution of monthly electricity consumption bills for the residential sector (ECRA, 2015)

Table 1.1: The current electricity tariff in KSA (SR/kWh)

Sector	End – 2015	Start – 2018	% Change
Residential: 1-6,000 kWh/month	0.05	0.18	260
Residential – above 6,000 kWh	0.30	0.30	0
Industry	0.18	0.18	0
Government	0.32	0.32	0

1.4 Impact of Electricity Consumption on the Environment and National Economy

KSA sits on the largest oil reserves in the world. Its oil reserve, which is estimated as 264.6 billion barrels, constitutes 19.8% of world's proven oil reserves. Oil accounts for 90% of KSA's exports and 45% of its GDP. This means that its economy is highly dependent on oil (Mansouri, Crookes & Korakianitis, 2013) and, in fact, it has been the largest producer and exporter of petroleum products in the world from the 1970's until 2013. In 2013, KSA became the second-largest petroleum liquids producer (behind the United States) and was the second-largest crude oil producer (behind Russia) (OPEC, 2014). KSA is also the largest consumer of petroleum in the Middle East and the world's twelfth largest consumer of the total primary energy source (i.e. petroleum and natural gas) as of 2013 (EIA-Website, 2013). The demand for fossil fuels for industry, transportation, power, and saltwater desalination in KSA will grow from about 3.4 million barrels of oil equivalent per day to about 8.3 million barrels of oil equivalent per day (from 2010 to 2028) according to estimates (IBP, 2015). On current trend, the consumption of domestic oil in the kingdom could reach up to 3,100 million barrels per annum in the next 15 years. Moreover, the advancement of shale and fracking technology in the US and the emergence of the US as a major oil producer are some of the important factors that have caused KSA and the world a major oil supply shock which that has led to a significant reduction in oil price since 2014 (Maugeri, 2013). In addition, the value of oil price is predicted to drop to SR 878.6 billion (over 11.3 % of GDP and 24% of government revenues) by 2030 and this could drastically reduce KSA's oil exports' potential (Taher & Hajjar, 2014). This could, sooner or later, have adverse effects on national development as fossil fuels will be in short supply (Mujeebu & Alshamrani, 2016).

Around 500,000 barrels of oil per day is used for electric power generation directly (Farnoosh, Lantz & Percebois, 2014; Mujeebu & Othman Subhi Alshamrani, 2015). It is therefore clear that the domestic electricity and, consequently, the oil consumption are increasing at a worrying rate. In addition, the burning of fossil fuels is largely responsible for pollution and environmental deterioration. In KSA, almost 50 % of the CO_2 emission is attributed to the electricity sector (Budaiwi, 2007). This contributes to the heat-trapping that is blamed for global warming. KSA is committed to maintaining its national contributions on taking climate actions that would enable sustainable development in line with the 2015 Paris climate change agreement (Clark, 2016). The distribution of KSA's electricity generation fuels from hydrocarbons is shown in Figure 1.9.

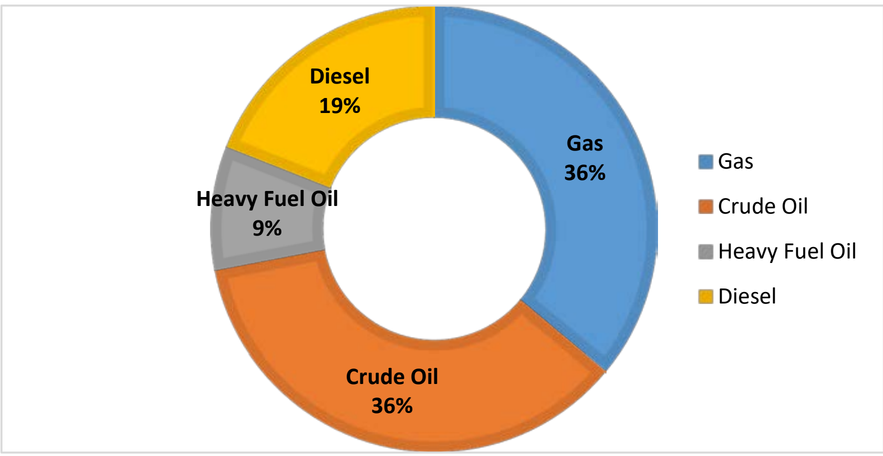


Figure 1.9: Annual Electricity Generation Fuels' Distribution in KSA in 2014 (ECRA, 2014)

1.5 National Electricity Policy

The development of KSA's electricity market is overseen by three major government entities: the Ministry of Water and Electricity (MOWE), and the Electricity and Co-Generation Regulatory Agency (ECRA) and King Abdullah City for Atomic and Renewable Energy (KACARE). MOWE sets and plans energy policies in the long-term for the electricity sector; it also oversees the investment of private companies in the sector as well as in the water sector. ECRA is the independent watchdog and standard setter for KSA's electricity industry, is responsible for assessing the tariffs, issuing the licenses, monitoring the service providers, investigating complaints, establishing quality of service standards and promoting fair competition among providers and suppliers. KACARE is responsible for driving the integration of clean energy sources and the development of energy efficiency programs and directives in the kingdom.

A number of goals that the Saudi government has set for the wider energy sector in order to drive investment in the country's electricity infrastructure and services includes (ECRA, 2015):

- reduce the amount of crude and natural gas-fired electricity generation;
- integrate solar energy supplies with electricity grid;
- interconnect the regional electric grids;
- increase the efficiency and reliability of electricity transmission and distribution;
- establish and develop nuclear power;
- work to achieve significant energy efficiency gains among residential, commercial, industrial and government consumers.

In 2005, KSA established the National Energy Efficiency Program (NEEP) in order to address environmental and energy issues (Alrashed & Asif, 2012). NEEP's activities include providing energy efficiency and technical training awareness programmes. The Saudi Energy Efficiency Centre (SEEC) was also established in October 2010 in order to meet the nation's goal of energy efficiency. SEEC's responsibility includes developing energy efficient technologies and conservation policies and creating awareness campaigns for households, among others (SEEC, 2017a).

Although still at the early stage of development, KSA is increasingly moving towards the exploitation of renewable energy resources as well as converting the existing electricity grid to a smart grid. These moves are prompted by the desire to manage the growth in peak demand and take maximum benefits from the advantages that are related to the use of the resources of renewable energy. KSA is the tenth largest in the world on production volume of CO_2 emission, which has adverse effect on public health and the environment (Marland, Boden & Andres, 2010). Moreover, the electricity generation sector accounts for 50% of the CO_2 emission in the country. The lack of a public transport system (i.e. the lack of alternative means of transport) has also been attributed to this high level of per capita oil consumption (Taher & Hajjar, 2014). Continued reliance on fossil fuels for power generation has harmful impacts on the nation’s economy and the global climate and environment. Prompted by the finite nature of oil and gas reserves, KSA plans to use its current wealth to prepare for the future. For a prosperous future, KSA has no choice but to develop strategies to reduce pressure on the oil sector by diversifying its economy and investing in managing its electricity sector using modern technological solutions such as smart technologies and renewable energy systems. Recently, KSA has seen many changes to energy policies and initiatives to reduce energy consumption of the residential sector because of the current plunge in oil prices which began in June 2014 and there is serious effort from the government to ensure that these policies succeed. For example, it plans to convert its vast desert into solar power (El-Katiri, 2014). In line with vision 2030 of KSA, the government has set for itself an initial target of generating 9.5 GW of electricity from renewable energy sources – solar and wind, in particular (Vision-2030-Website, 2018).

1.6 Aim and Objectives of Research

The rapid growth of electricity demand and consumption in KSA’s residential sector is a serious problem in need of urgent and practical solutions. The surge in demand due to the energy consumption of AC during the summer is a pressing issue that needs to be addressed.

Employing suitable operation strategies such as turning on AC systems at times when buildings are occupied have been proposed for KSA buildings such as mosques but no study has covered residential buildings on a large scale. Importantly, so far, the potential for reducing peak electricity demand through better control of domestic AC systems has not been explored in the literature on this subject. This requires an understanding of how domestic AC systems are typically operated in KSA at present and, at the same time, the knowledge of the thermal properties of typical residential buildings in KSA. An analysis drawing on demographic and behavioural data with respect to the use of AC and the design of residential building is therefore required.

Use of renewable energy systems, such as PV systems, during the peak time of electricity demand is widely known in the literautre. However, optimizing the tilt and azimuth angles of PV solar panels so that it takes into account the shape of the peak demand profile to maximise amount of power that produced by the solar systems at the time when electricity demand is at its peak has not been studied so far in the case of Saudi Arabia. Studies so far have also not taken into account the optimization of the angles with respect to the effect of dust accumulation of the solar panels – which is important for countries with a desert-like climate like KSA.

While KSA has high potentials for developing energy production via Solar Water Heating (SWH) systems, so far it has not taken advantage of this technology. In fact, analysis on the reduction in peak electricity demand achievable when domestic hot water is supplied using SWH systems for KSA's households has not been done. Thus, despite the recognition of SWH systems as a renewable energy source, their potential to mitigate peak electricity demand in the case of KSA has not been appraised.

Presenting a framework for addressing the challenging problem of the increasing electricity consumption in KSA through smart grid solutions to manage the operation of AC systems and the exploitation of the renewable energy systems, PV and SWH systems in particular, is the focus of this thesis. A comprehensive literature review on previous work relevant to the reduction of electricity consumption in KSA including more details on the research gaps are given in Chapter 2 and in the individual chapters addressing each of the presented solutions.

In summary, this research proposes some of the most applicable solutions to manage the peak electricity demand of the residential sector that conforms to national strategies and policies. It does so by taking advantage of renewable energy technologies and integrated smart grid options.

1.6.1 Research Aim

The main aim of this research is to investigate and compare smart grid solutions that deliver energy generation and electricity demand management at the distribution network level, in order to reduce the peak electricity demand of KSA that is supplied by large-scale fossil fuel generation plants.

1.6.2 Research Objectives

The research objectives are as follows:

1. Investigate the deployment of PV panels with a slope and orientation that optimises their output with respect to the timing and shape of the demand profile taking into account the reduction in the performance of solar PV systems due to the accumulation of dust.
2. Establish operational strategies for residential AC by appropriately managing electric load of AC on the demand side through smart scheduling and control.
3. Develop operational strategies for residential AC under control of the utilities to remotely set thermostats.
4. Investigate the deployment of solar thermal systems as a source of domestic hot water to reduce the use of electric water heating systems.
5. Investigate the scalability and effectiveness of each of the proposed solutions in order to estimate the potential reduction in peak grid electricity demand that will be achievable as a result of combining these solutions.

The deployment of the PV systems and the solar thermal water heating systems are to supply energy while the smart scheduling and control or remote control of AC system are to manage the energy consumption on the distribution network. A block diagram representing an overview of this research is given in Figure 1.10.

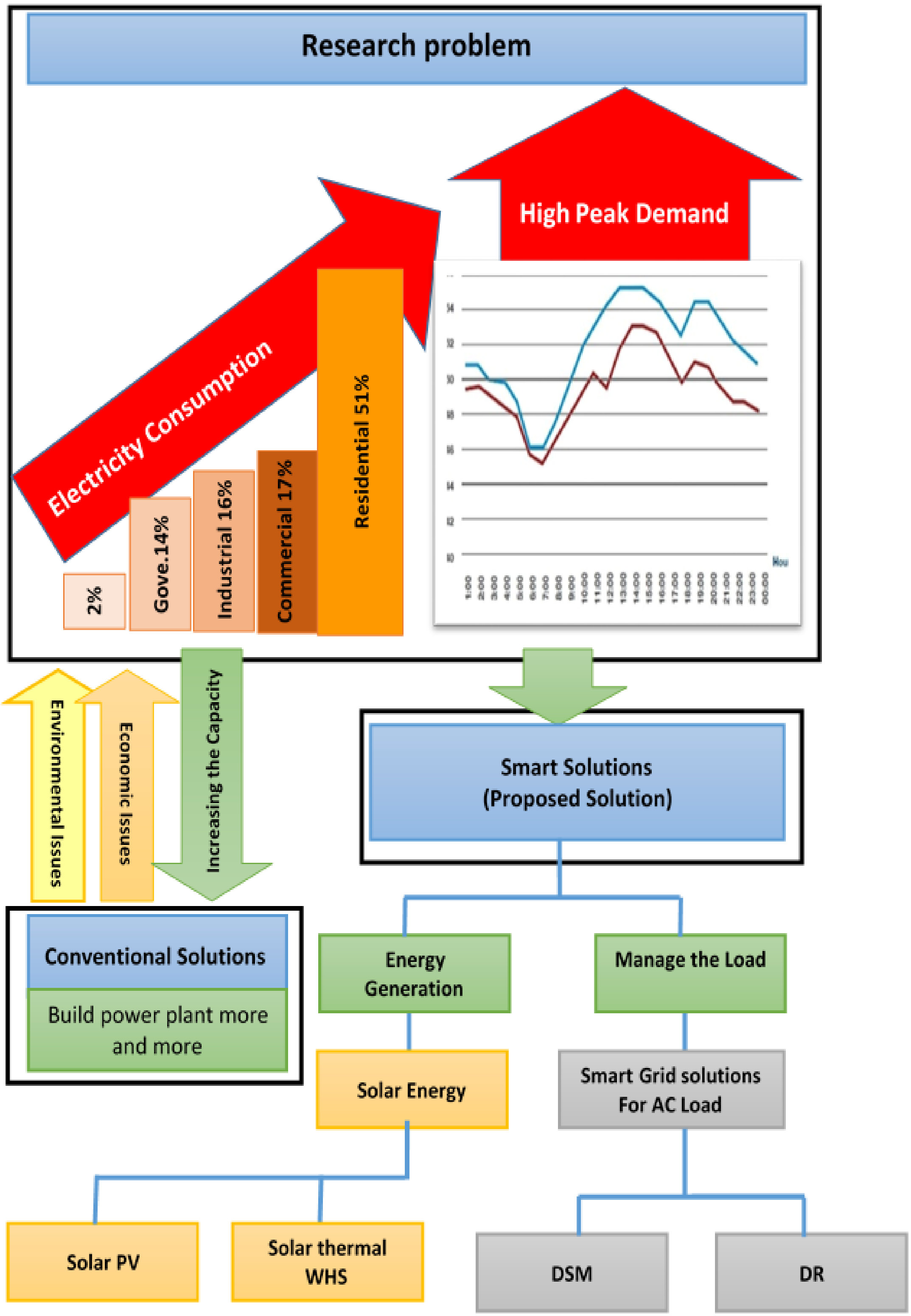


Figure 1.10: Block diagram representing the overview of the study

1.7 Thesis Structure

In chapter 1, the geographic location, population, growth, and climate of KSA have been described. The growth of the electricity market and the prediction of future energy needs have been presented. The role that air conditioning systems play in the overall electricity consumption was emphasized. Increasingly, KSA is moving towards the exploitation of renewable energy resources and the need to manage the growth in peak demand through the use of renewable energy resources has been broadly introduced. In addition, the chapter motivates the overall objectives of this thesis. The structure and flow of the thesis follows.

Chapter 2, presents a literature review including recent advances and research on the techniques and strategies relevant to the reduction of electricity consumption in KSA. Areas that have not been adequately treated so far within the research community are also identified. The chapter also reviews literature on the energy consumption of air conditioning systems, solar PV systems, and solar thermal energy systems.

Chapter 3, titled, 'Deployment of Photovoltaic Systems in Public Buildings', is to present one of the possible ways of managing electricity peak demand by proposing the deployment of PV panels with slope and orientation that are optimized with respect to the shape and timing of the demand profile in order to contribute most effectively to national electricity generation capacity. As a case study, numerical results are presented for Riyadh city in KSA. In countries with desert-like climates like the KSA, dust accumulation on PV solar panels plays a major role in the amount of energy that can be harvested from solar PV systems. The analysis of the chapter, therefore, also covers the optimization of the slope and orientation of PV solar panels taking into account the reduction in the performance of solar PV systems due to the accumulation of dust.

Chapter 4, titled, 'Reducing High Energy Demand Associated with Air-conditioning Needs in KSA', is to investigate some solutions to the problem of high energy demand associated with air-conditioning needs in KSA in residential building. It is clear that improvements that will effectively encourage reduced operation of air-conditioning units will affect savings in the total energy consumption of these buildings. These savings are particularly important during the peak duration of electricity demand. Typical residential buildings of KSA are therefore modelled and simulated using the DesignBuilder software in order to understand the different proposed solutions in the form of modes of operations of AC that can effectively reduce the energy consumption of air conditioning units. The potential impacts in terms of the achievable electricity savings of the different modes of AC operation for the residential houses of Riyadh city are presented. In addition to using data of the typical house types and their actual dimensions and building materials, the simulation takes into account typical behaviour of occupants of residential buildings in Riyadh city making use of behavioural data obtained through a survey that was carried out.

Chapter 5, titled, 'Water Heating Systems', focuses on the reduction in peak electricity demand achievable when domestic hot water is supplied using SWH systems. A case study of Riyadh city in KSA is presented in particular to determine the electricity demand reduction that can be achieved from SWH deployment. This can encourage the government to popularize the use of SWH systems and decide how far to support an intervention (such as through initiating subsidy programs) that will encourage their usage. Factors influencing the volume of hot water consumption in KSA include climatic factors, human behaviour, house types, electricity consumption, and household income. The chapter also presents an estimate of hot water requirement for household with different number of members.

Chapter 6, further discussion on the solutions proposed in this research including their effectiveness, their large-scale deployment and their possible combination is presented. The findings are broadly applicable to other countries, particularly those in the Middle East, with similar climatic conditions and electricity usage behaviour and patterns. Moreover, benefits of the reductions of electricity demand during peak time have been benchmarked against the current situation in KSA.

Chapter 7, the thesis summary, findings, contributions, recommendations and further studies that could be investigated by other researchers in the future are presented.

The structure of the thesis as described in the section is represented in Figure 1.11.

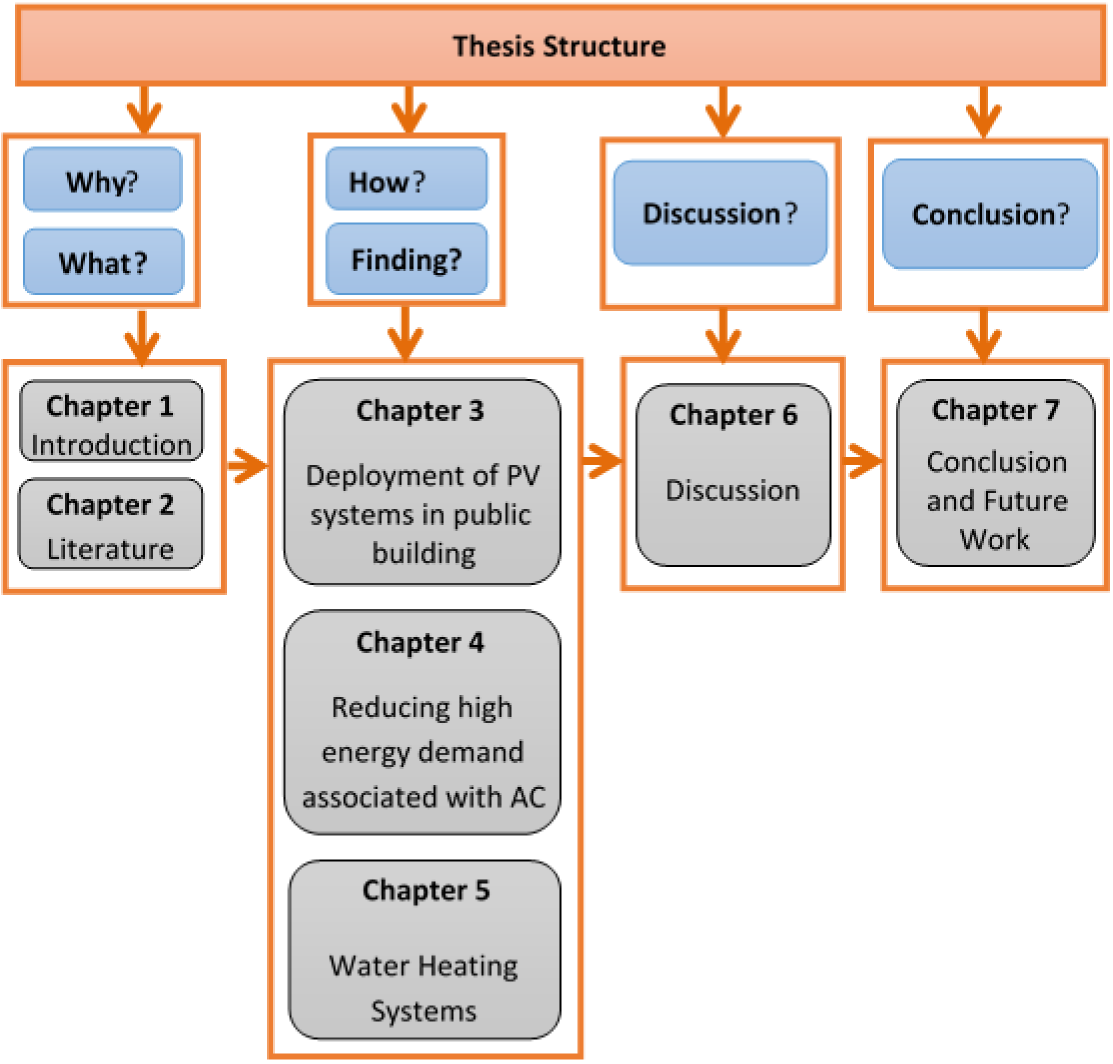


Figure 1.11: Structure of the thesis

Chapter 2: Literature Review

2.1 Introduction

This chapter presents a literature review including recent advances and research on the techniques and strategies relevant to the reduction of electricity consumption in KSA. Areas that have not been adequately treated so far within the research community are also identified. In the sections that follow, literature reviews on solar PV systems, the energy consumption of air conditioning systems, and solar thermal systems are presented. These reviews are later extended in the individual chapters addressing each of the three solution topics.

2.2 Solar Photovoltaic Systems

In KSA, due to the availability of solar radiation energy, which is between 2000 kWh/m^2 and 2200 kWh/m^2 on the average for its annual 3245 sunshine hours per annum (Alawaji & Hasnain, 1999)), there is a huge potential for using solar radiation energy (Pazheri *et al.*, 2012; Rehman, Bader & Al-Moallem, 2007). Indeed, photovoltaic technology has been shown to be a simple and yet effective means of energy generation in KSA (Rehman, Bader & Al-Moallem, 2007). For instance, some recent reports on the usage of PV technology in KSA include the integration of PV in to the envelope of buildings (such as roofs of houses and hospitals) while at the same time employing energy-efficient structures and materials for the remaining components of the building (Mujeebu & Alshamrani, 2016; Mujeebu & Othman Subhi Alshamrani, 2015; Appelbaum, 2012).

Solar energy research in KSA has been growing since the late 1960s, when small-scale university projects were conducted, and the late 1970s, when major research and development works were initiated by the King Abdulaziz City for Science and Technology and the joint agreement for cooperation in the field of solar energy between KSA and the US under the Saudi Arabian – United States Program for cooperation in the Field of Solar Energy Program (SOLERAS) (Lowenstein & Smith, 1979; Alawaji &

Hasnain, 1999). The SOLERAS program led to the development of prototype projects for applications ranging from agriculture (e.g. crop/fruit drying, irrigation pumping, etc.) and electricity generation to cooling and water desalination (Alawaji, 2001a; Alawaji & Hasnain, 1999).

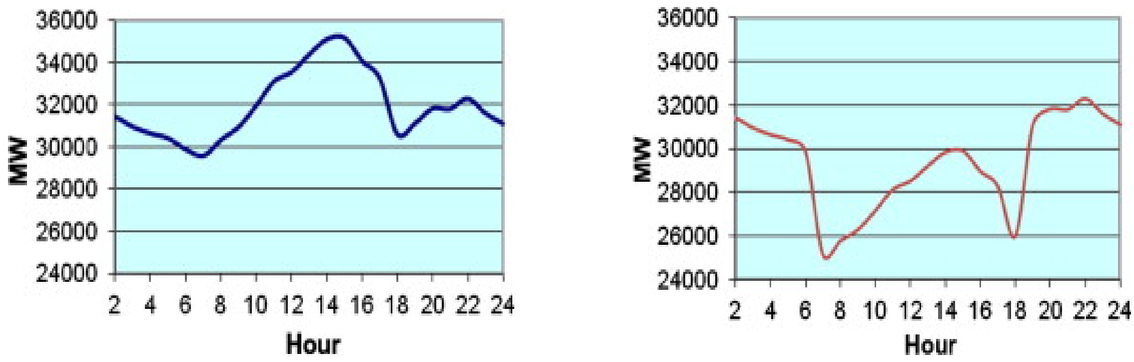
Between 1978 and 1998, KSA undertook a significant number of projects related to the development and utilization of renewable energy sources (Rehman & Halawani, 1998). The experience gained during this period in the assessment, instrumentation, analysis, collection of data, monitoring and calibration had been valuable and have assisted many projects on solar energy throughout the country thereafter (Alawaji, 2001b).

The most important element of any PV system is the solar module, which consists of several individual PV cells that are connected in series or in parallel. In general, the number of individual cells of a module and the cells' arrangement (series or parallel) determine the energy produced by a PV module. To produce a specific amount of voltage and current, several modules are arranged to form a solar array (Rehman, Bader & Al-Moallem, 2007). An example of an important solar project executed in KSA is the Solar Village Project (Alawaji, 2001a). The Solar Village Project (which is located 50 km northwest of Riyadh) was started in the late 1970s for research purpose and has its own dedicated weather-data monitoring station. A 3 kWp PV project, relevant to studying effects of changing directional variation, rotation, long-term dust and dirt accumulation, as well as PV measurements (e.g. efficiency and power output), was also installed in the Solar Village for research purposes, Another 6 kWp PV power system was installed to carry out these studies as well as evaluate the integration of PV power system into an electric grid – particularly for load levelling reasons during the peak times (Huraib, Hasnain & Alawaji, 1996; Smiai & Alawaji, 1994; Almasoud & Gandayh, 2015).

Also, KSA's installations of PV systems are sometimes application oriented; for instance, PV systems have specifically been designed for desalination plant equipment (Alawaji *et al.*, 1995), for a combination of water pumping (for storage of water in tanks for later use) and desalination (Alajlan & Smiai, 1996), for university campuses (Rehman, Shash & Al-Amoudi, 2006), and for schools, mosques and wild-life protection (Alawaji, 2001a), among others.

Various types of solar PV systems are now being used in KSA include concentrated solar PV power system (Salim & Eugenio, 1990), PV-thermal system (a hybrid of two methods: one method involves sunlight beam being directly converted into electricity and the other method converts dissipated heat of the sun into heat for specific applications) (Al Harbi, Eugenio & Al Zahrani, 1998) and hybrid PV-wind or wind-PV-diesel power system (Shaahid *et al.*, 2010). Research has been carried out into hybrid PV-diesel systems for residential and commercial buildings (Shaahid & Elhadidy, 2003, 2004), into PV system designs specifically for hospital buildings (Appelbaum, 2012), into grid-connected solar-roofed house design (Tan & Maerten, 2011), and into electrical and thermal modes for solar air conditioning (El-Shaarawi *et al.*, 2013; Al-Mogbel *et al.*, 2013; Sofrata & Abdul-Fattah, 1982).

The load pattern of electricity in KSA during summer based on the study given in (Almasoud & Gandayh, 2015) is shown in Figure 2.1 (a). The resulting load pattern when PV solar plant is adopted with peak saving of electricity plot is given in Figure 2.1 (b) was obtained based on the assumption that the whole of KSA's land area can be converted into electricity with the exception of areas (such as areas of sand dunes and shifting sands – which, I n total, constitute 20 – 30% of KSA's land area) that are not suitable for PV solar panels' installation due to their geomorphological features. Clearly, apart from geomorphological features, there are many areas (such as industrial plants, major roads, agricultural areas, etc.) that it will either be impossible or impractical (due to, for instance, the current state of solar PV technologies or the significant amount of the installation cost) to install solar panels which the study has not taken into account. Moreover, if the assumption of the whole area is indeed applied, the obtained power will be more than peak requirement of KSA and the extra power can be exported to other countries (Ghafour, 2011). Thus, the conclusion reached by the study is unrealistic and impractical. Importantly, the results (refer to Figure 2.1 (b)) does not appear reliable due to the unaltered nature of the shape of the demand curve during peak period. However, the valuable lesson from that study is that, energy demand on a given day reaches its peak between 12:00 noon and 5:00 pm (which agrees with ECRA's report referred to previously in Chapter 1; see Figure 1.2). This current study will demonstrate (in Chapter 3) that photovoltaic (PV) generation can provide additional supply of electricity during this peak demand time.



(a) (b)

Figure 2.1: (a) The load pattern of electricity, and (b) the resulting load pattern when PV solar plant is adopted (Almasoud & Gandayh, 2015)

2.3 Energy Consumption of Air Conditioning Systems

There are several strategies that can be used to achieve savings in AC electricity consumption for KSA; these include:

- The design and construction of energy efficient building through proper insulation and control of ventilation.
- Improving the efficiency of the air conditioning systems themselves.
- Operational strategy and control of the AC.

These strategies are further elaborated upon in the subsections that follow.

2.3.1 The Design and Construction of Energy Efficient Building through Insulation

In recent time, there has been rapid increase in the population as well as economic growth in KSA. Consequently, the nation’s residential buildings have gone through a rapid expansion although serious consideration of the energy efficiency of these buildings is lacking in general. Weaknesses have been identified in the architectural design of the buildings that encourages excessive energy consumption of the AC. For instance, there is a lack of proper shading strategies for the buildings and the shape of the buildings unfavourably affects solar heat gain (Aldossary, Rezgui & Kwan, 2014, 2015). About 52% of respondents’ houses assessed in a survey carried out in KSA were identified to be inadequately insulated (Aldossary, Rezgui & Kwan, 2015). In order to successfully bring about the construction of energy efficient buildings, climate-responsive and environmentally friendly building design technologies are recently being considered (Omer, 2008; Taleb & Pitts, 2009).

According to Saudi Energy Efficiency Centre (SEEC), the challenges that have been identified and that need to be tackled in order to save significant amount on energy costs in residential buildings include (Mujeebu & Alshamrani, 2016):

- The lack of thermal insulation in 70% of residential buildings.
- The low energy bills (due to the nation's highly subsidized energy sector) do not motivate investment in energy efficient buildings.
- The lack of use of low energy efficient products due to the lack of awareness on the importance of energy efficiency.
- The weakness of product control standards.

Due to the lack of thermal insulation in most residential buildings, retrofitting insulation to these buildings can be suggested as a solution to this problem. Also, high thermal mass (as used in traditional KSA construction) would mitigate temperature peaks. However, that would require a major and laborious task and will take many years (of course, measures for proper and better insulation, such as improvements in the architectural design for better energy efficiency, could be put in place in future residential building projects). Other measures that can address the challenges due to high energy consumption of AC more quickly are the focus of this thesis.

2.3.2 Improving the Efficiency of Air Conditioning Systems

Reduction in the consumption of energy can be achieved by reducing the energy usage of the AC systems themselves. Strategies to accomplish this energy reduction include (Al-Ajlan *et al.*, 2006): those involving retrofitting existing AC, those involving developing new AC systems manufacturing designs (such as, for instance, increasing the number of condenser rows which has been shown to be one of the best ways of achieving a higher Energy Efficiency Ratio (EER) (Al-Shaalan, 2012)), and those that do not involve adapting the existing AC at all (such as employing suitable operational strategies of AC which could reduce up to 23% of energy consumption (Budaiwi, Abdou & Al-Homoud, 2002; Budaiwi, 2007)).

Each of these strategies currently has its own major drawback. For example, retrofitting existing AC can be inconvenient and laborious for many users, and newly designed AC can be purchased and installed in old and new buildings but the challenge of buying and installing new AC in all old buildings still persists. Employing suitable operation strategies such as turning on AC systems at times when buildings are occupied have been proposed for KSA buildings such as mosques but no study has covered residential buildings or sector, which is a major sector for energy consumption, on a large scale as far as this author is aware. In this thesis, findings will be presented on suitable operational strategies of AC for new and old residential buildings alike in KSA that will lead to significant energy savings for the electricity customers and do not involve retrofitting or adapting their existing AC.

2.3.3 Operational strategy and control of the AC

A major contributor to high electricity consumption is occupant behaviour. Many customers in KSA leave their air-conditioning units to run non-stop throughout the summer months (Taleb & Sharples, 2011; Mujeebu & Alshamrani, 2016). Thus, 73% of households in KSA turn on their air conditioning systems from between 10 to 24 hours on a typical day during the summer months according to survey conducted across the country and presented in (Aldossary, Rezgui & Kwan, 2015). A significant amount of energy saving can be achieved even by a small increase of AC thermostat settings e.g. 1^{o}C or 2^{o}C (Vine, 1986; Maheshwari *et al.*, 2001). These savings are particularly important and desirable during the peak duration of electricity demand. The setting of the thermostats to one value throughout the summer and to another value throughout the winter (with the two values determined by averaging the daily optimal values) can significantly reduce air-conditioning loads and increase energy savings (which could reach billions of dollars in cost reduction at national level (Lu *et al.*, 2010)) while still achieving the desirable thermal-comfort for occupants (Al-Sanea & Zedan, 2008).

Demand Side Management (DSM) is the adjustment of consumer energy demand through customer behavioural change as a result of education or financial incentive. The goal of DSM is primarily to encourage customers to use less energy during peak hours, which is often achieved by moving the time in which energy is used to off-peak times such as early morning, evening, or weekends. In addition, Demand Response (DR) is the technology that enables economic rationing system through the adjustment of consumer energy consumption by the electric utilities for the better matching of consumer demand with the energy supply. To achieve this, utilities offer low price of electricity for consumers during off-peak hours and high price of electricity during peak periods. Through DR, utility companies and customers save cost and energy. Comprehensive literature reviews on DSM and DR are given in Chapter 4 of this thesis. The few paragraphs that follow only present a summary of relevant literature on these subjects that are related to KSA.

In order to achieve DSM in KSA, some researchers have proposed the use of thermal energy storage systems that will store energy for use during peak periods thereby for shifting AC load to reduce the peak electricity demand (McLorn, Sheikh & Rob, 2014; Hasnain & Alabbadi, 2000). Simulation analysis of the residential buildings equipped with such thermal energy storage systems and using historic electricity demand data given in (McLorn, Sheikh & Rob, 2014) demonstrates promising potential of this technology. However, the technique may be applied in commercial, industrial and government sectors but it will be impractical for residential sector due to the lack of efficiency in the production of ice during the night when electricity demand is low for use at the peak period during the day.

DSM for university campus in KSA has also been proposed. In (Jomoah, Al-Abdulaziz & Kumar, 2013) for example, investigates DSM through the installation of energy management system that continuously monitors the electrical load demand of the ACs and room lighting of the university buildings. The system sets the thermostats of the ACs based on daily work schedule and the results showed promising potential for energy consumption reduction. However, university campus buildings (containing classrooms, offices, lobbies, and conference hall with each group equipped with several occupancy sensors) were considered; given that these buildings are much larger than residential buildings and they generally have predictable daily working hours. For residential buildings, a thermostat that learned occupancy patterns, e.g. with activity sensors, could determine an efficient schedule automatically.

As for DR, studies have shown that DR programs are capable of reducing the system peak by up to about 9% (Maqbool *et al.*, 2011; Taqqali & Abdulaziz, 2010; Faruqui & Sergici, 2010). Examples of the price-based DR programs are the real-time price (RTP), the critical-peak price (CPP) and the time-of-use (ToU) programs. Recently, DR is being proposed for KSA (see (Aljahdali, Fahad and Abbod, 2017)) as a way of managing energy consumption. In particular, the impact of the ToU pricing option for customers in KSA is studied in (Matar, 2017) where it was reported that with ToU, the utilities will be able to realize higher profits from the residential sector and will effectively be able to reduce the high level of energy demand from the sector. Some of the challenges of the DR approach when extended to residential sector include finding the optimum schedule and the ICT infrastructure that can be deployed to actualize DR (Haider, See & Elmenreich, 2016; Adika & Wang, 2014; Darby & McKenna, 2012) and satisfying the objective of minimizing customers' energy cost based on the utility companies' energy availability is the key requirement (Haider, See & Elmenreich, 2016). Some of the issues that are being raised by current research in DR include customer inconvenience and responsiveness for different DR programs (Gyamfi, Krumdieck & Urmee, 2013) and the effect of different tariffs on the level of responsiveness (Hamidi, Li & Robinson, 2009). It has been shown that a large number of customers do not respond to price by changing their consumption behaviour and this must be considered when designing DR schemes in general (Haider, See & Elmenreich, 2016; Gyamfi, Krumdieck & Urmee, 2013). In addition, it has been reported that certain types of domestic appliances are good candidates that can provide DR (Hamidi, Li & Robinson, 2009). In practice, it is not required that all customers respond simultaneously to take advantage of DR. In fact, it has been suggested that only 5% of all customers are needed to curtail electricity market price although up to 20% of customers can account 80% of the price response (Mohagheghi *et al.*, 2010).

None of the studies carried out in relation to KSA dealt with daily electricity consumption pattern of customers in residential buildings which is crucial in understanding the short-term (e.g. intermittently entering and leaving a room or home, moving from one room in a house to another, or leaving the house for work, etc.) and the long-term (such as business trips, illnesses and holidays) occupancy behaviour for such buildings. Such occupancy information allows occupancy prediction which is very important for scheduling and controlling the buildings' climate (Oldewurtel, Sturzenegger & Morari, 2013). The ability to predict both short- and long-term vacancies can provide meaningful energy savings (Bloomfield & Fisk, 1977). Simulation results that can be produced using building models and simulation software can only be as good as the ability of such models to accurately predict occupancy behaviour of the buildings to a large extent (Kwok & Lee, 2011). Thus, for this thesis, a survey has been undertaken to investigate some of the behavioural factors causing high-energy consumption in Saudi Arabia's domestic buildings. Also, measurements of household-level electricity consumption from the different types of housing units in KSA were undertaken. Using both qualitative and quantitative research methods, a statistical impression of the current occupancy behaviour has been obtained. The survey's questionnaire was designed and distributed to people of different gender and regions across Saudi Arabia in order to obtain information related to building design, occupants' behaviour with regard to electricity use, and perception on renewable energy. With the insights gained from the survey, novel and practical approaches of reducing energy consumption in KSA's residential buildings without compromising indoor air quality and comfort of occupants will be proposed.

2.4 Thermal Solar Panel for Water Heating Systems

Solar thermal systems, or solar water heating (SWH) systems, can be a better alternative as a source of hot water to the use of electric water heating systems in many countries where electric water heating systems are still dominant (Abd-ur-Rehman & Al-Sulaiman, 2016; DECC, 2013). The hot water generated from SWH systems finds use in many sectors of the economy including domestic, commercial, and industrial sectors (Veeraboina & Ratnam, 2012). SWH systems are increasingly being used worldwide (Weiss, Spörk-Dür & Mauthner, 2017) and their deployment vary significantly from country to country as factors such as policy, culture, and energy cost play a great role in the acceptance of SWH technologies (Leidl & Lubitz, 2009).

The efficiency of solar to thermal energy conversion (with SWH systems) is much greater than the efficiency of solar to electricity conversion (i.e. solar PV systems (Jaisankar *et al.*, 2011) (Gul, Kotak & Muneer, 2016). The SWH technology requires minimal number of panels (2-3 panel) and less space compared to other solar energy applications, and the technology is both reliable and economical for hot water production (Chang *et al.*, 2009).

SWH can be used to address the problem of reducing energy consumption in KSA. KSA's vast open land that receives huge amount of solar radiation is particularly suited for solar thermal energy conversion applications and, recently, studies have been carried out to demonstrate the most suitable locations in KSA for solar thermal water heating technologies (Abd-ur-Rehman & Al-Sulaiman, 2014) but in reality solar water heating can work anywhere in KSA. Solar thermal plants are also currently being built for domestic heating and hot water purposes in KSA. In fact, the largest solar thermal system in the world was built in KSA (in Nora University in the city of Riyadh) in 2011 (Mujeebu & Alshamrani, 2016).

In KSA, the share of water consumption per capita has increased from 237 litres per day in 2010 to 253 litres per day by 2014, a growth rate of 8 percent, and it reaches 266 litres per day in 2017 (Islam, Sumathy & Khan, 2013; General Authority for Statistics Kingdom of Saudi Arabia, 2017). A reasonable amount of energy can therefore be saved by using solar water heating systems since solar thermal energy is free although they require an initial cost to buy and install which will be paid back in the bills from the electricity savings that will be achieved over time.

While KSA has high potentials for developing energy production via SWH systems, so far it has not taken advantage of this technology to a large extent for increasing its energy generation and reducing peak electricity demand. In fact, analysis on the reduction in peak electricity demand achievable when domestic hot water is supplied using SWH systems for KSA is not available to the best of the author's knowledge as at the time of writing this report. Thus, despite the recognition of SWH systems as a renewable energy source, their potential to mitigate peak electricity demand in the case of KSA has not been appraised.

More generally, most countries of the Gulf Cooperation Council (GCC) in the past do not have policies that seriously encourages the usage of solar thermal systems – largely due to the greatly subsidized price of electricity and the abundance supply of energy from fossil fuels (Al-Badi, Malik & Gastli, 2009; Abd-ur-Rehman & Al-Sulaiman, 2016); however, with the current price of crude oil and the depletion of fossil fuels, these countries are beginning to look into renewable energy systems as a viable alternative for meeting their increasing energy needs.

Importantly, the efficiency of solar energy systems peaks in the summer and the energy demand of KSA is greatest during this period; therefore, the deployment of WHS systems can be used to reduce peak energy demand. This research work will therefore investigate the amount of energy that could be saved by deploying thermal solar energy systems for domestic water heating in typical houses in KSA.

2.5 Summary

In this chapter, a literature review on previous work relevant to the reduction of electricity consumption in KSA has been presented including current challenges in this research area. The lack of previous studies on the employment of suitable operation strategies for AC systems covering residential buildings or sector on a large scale, the absence of literature on the optimization of solar panels' tilt and azimuth angles so that the time of maximum output of PV solar plants matches the time of peak energy demand and taking into account the effect of dust accumulation, and the lack of appraisal in the literature of SWH as a potential renewable energy source that can mitigate electricity demand during peak time are some of the identified research gaps. In particular, details related to the energy consumption and reduction potential of solar PV systems, air conditioning systems, and solar thermal energy systems are given. In the next few chapters, frameworks for addressing the challenging problem of the increasing electricity consumption in KSA through smart grid solutions to manage the operation of AC systems and the exploitation of these renewable energy systems are presented. Each of the chapters will also present a more elaborate literature review of the energy system solution it presents.

Chapter 3: Deployment of Photovoltaic Systems in Public Buildings

3.1 Introduction

This chapter presents one of the possible ways of managing electricity peak demand by proposing the deployment of PV panels with slope and orientation that are optimized with respect to the shape and timing of the demand profile in order to contribute most effectively to national electricity generation capacity. As a case study, numerical results are presented for Riyadh city in KSA. In countries with desert-like climates like the KSA, dust accumulation on PV solar panels plays a major role in the amount of energy that can be harvested from solar PV systems. The analysis in this chapter, therefore, also covers the optimization of the slope and orientation of PV solar panels taking into account the reduction in the performance of solar PV systems due to the accumulation of dust.

The subsequent sections are arranged as follows: a literature review on solar PV and tracking systems, on tilt and azimuth angles optimization and on effects of dust on solar PV systems is presented in Section 3.2. Theoretical background (that is, equations governing PV systems) is presented in Section 3.3. The estimate of the area of government buildings in the form of malls, mosques and schools that is available and can be used for the installation of solar PV panels is presented in Section 3.4. The algorithm for finding the optimum orientation is given in Section 3.5. This algorithm will be used to find the optimum tilt and azimuth angles that take into account the shape of the energy demand profile given in Figure 1.2, so that the maximum amount of electricity is produced by the PV systems when electricity demand is at its peak. The section also presents numerical results for the case study of Riyadh city with discussions on the results of setting the tilt angle to suboptimum values such as to the latitude of the location of the PV system, to the average of optimum tilt angle for the five summer months and for the other seven months and to the value for which yearly maximum energy. The results of the matched and unmatched cases of finding the optimum tilt angles when a PV system is adopted for electricity generation are compared. Section 3.6 presents the numerical results where the effect of dust accumulation is considered in the optimization algorithm. The chapter summary is given in Section 3.7.

3.2 Photovoltaic Systems: A Review

3.2.1 Background

The conversion of sunlight to electricity, first demonstrated as a practical technology using a silicon semiconductor junction by D. Chapin, C. Fuller and G. Pearson of the Bell Labs in 1954, is accomplished through PV solar cells. The power produced by a solar module, under Standard Test Conditions (Krüger & Kravchik, 2017), is known as the Peak Watt (Wp) rating. Due to variations in cloud cover and solar radiation over the day, temperature and other factors, the average electrical energy that can practically be obtained from a PV solar cells is often much lower than its Wp rating.

The relative position of the earth and sun is often represented using the celestial sphere around the earth so that, at the celestial equator, the equatorial plane intersects the celestial sphere. The earth revolves around the sun in an elliptical orbit and is tilted at an angle of 23.46^{o} with respect to the celestial equator. The angle between the line that joins the centres of the earth and the sun and its projection on the equatorial plane is known as the solar declination angle (δ). The instantaneous position of the sun as observed on earth (with respect to the earth's own polar axis) as the earth rotates around its own polar axis (at the rate of one revolution per day) is defined as the solar hour angle (ω) whose value is zero at the solar noon (with the time before and after expressed as negative and positive degrees, respectively).

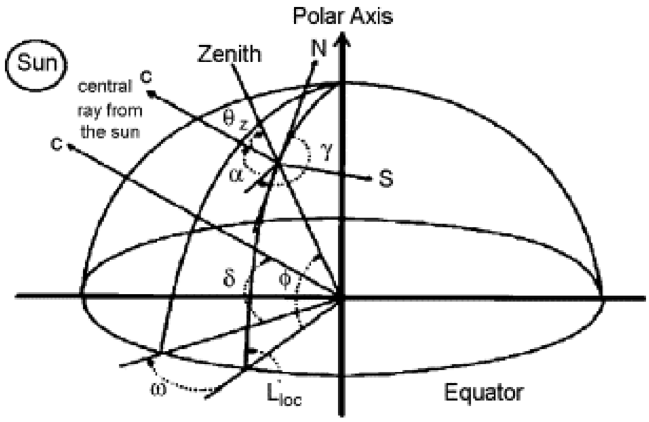


Figure 3.1: PV orientation's angles (Mousazadeh *et al.*, 2009)

The energy from the sun that reaches a surface on the earth directly is referred to as the direct or beam radiation. The incident energy from the sun as it enters the earth's atmosphere that is scattered or absorbed by air molecules and aerosols before reaching the surface is called the diffuse radiation (Mousazadeh *et al.*, 2009).

Solar radiation is one of the most important parameters that affect solar PV performance by determining the electric energy output. In turn, the tilt angle (the angle between the plane of the PV panel's surface and horizontal) and orientation (the direction of the PV panel's surface with respect to sun) affect the solar radiation a PV panel receives. As the position of the sun with respect to the earth is not constant all year round, tracking systems can provide instantaneous optimal tilt angle and orientation for positioning PV panels (Zhao, Wang & Goel, 2010). Solar sun-tracking systems are devices that are designed to keep solar panels (PV or thermal) in an optimum position (for instance, perpendicular) to the solar radiation during the daylight hours. In general, although solar trackers have the ability to boost the performance of solar PV systems, important challenges that must be considered before their adoption include energy consumption, cost, reliability, maintenance, and performance. Thus, from a practical viewpoint, solar trackers are not likely to be used for either for large or small PV generating plants, due to the cost related to the mechanical components and maintenance (Kerr, 2018). Consequently, it is very important to design PV systems so that the fixed tilt angle and orientation are optimized.

3.2.2 Tilt Angle and Orientation of Solar PV Systems

The amount of solar radiation that a PV panel receives is influenced in the short term, for instance, by cloud density and rain fall and in the long term, for instance, by the climate at the location of the PV panel. A lot of research work has been carried out in order to determine the optimum tilt angle required to receive maximum solar radiation. However, most of these works involve specific location (e.g. Cyprus (Ibrahim, 1995), China (Tang & Wu, 2004), Turkey (Kacira *et al.*, 2004; Gunerhan & Hepbasli, 2007), and Egypt (Morcos, 1994)) and optimum tilt angle for specific periods of time ranging e.g. one month, several months, one year and so on.

Several methods have been proposed in the literature for obtaining the optimum tilt angle; one of these is the radiative transfer method (Smith, Forster & Crook, 2016). This globally applicable and computational method uses meteorological data (which can come from satellite observation centres), such as cloud liquid and cloud ice water paths, water vapour, cloud fraction, surface albedo, temperature and ozone, to predict the optimum tilt angle of the location of interest. Although, this method can be useful where other ground measurements of tilted irradiance are not available, the model does not include a validatation against tilted irradiance measurements from a large network (i.e. globally) due to a lack of high-quality tilted irradiance measurement stations. Another method, given by Li & Lam, (2007), uses a numerical approach to calculate the solar radiance data for finding the optimum tilt angle by integrating the measured sky radiance distributions. This numerical method can be used to determine the monthly solar radiations at optimal tilt angles for many locations around the world where the local data on solar radiation for the surfaces of interest are not readily available.

A method for determining optimum tilt angle for PV systems in building applications is given in (Gunerhan & Hepbasli, 2007) where the optimum value for a particular day is calculated by searching for the angle that gives the maximum output for that particular day. An application of this mathematical modelling method was demonstrated using experimental data of a location in Turkey. It was highlighted that the solar panel should be adjusted to monthly optimum tilt angle (obtained by taking the average of the optimum tilt angle for each day of the month) once a month to give high efficiency. However, the study does not consider the cost of employing the labourers for carrying out the monthly adjustment of the PV panels. If this cost is significant, it could make the payback period for PV installation very long or even make the cost of installation and running as a solar PV power plant costlier than conventional energy generations. It would also be useful to know the effect of adjusting the PV panels for a lesser amount of time per year (e.g. three times in a given year) and compare the power output as well as the cost of labour to that of the monthly adjustment suggested in the study. Also, the study does not take into account the effect of accumulation of dust when estimating the optimum tilt angle. Dust particles can have detrimental impact on the output of PV systems and it is very important to take this into account when finding the optimal tilt angle for PV systems. A comprehensive discussion on the effect of dust accumulation on PV systems will be presented later in this chapter.

Researchers have proposed experimental methods for determining optimum tilt angle. In general, these methods involve measuring maximum energy output for a given period (e.g. a year), often with several PV modules, and then fitting the data obtained into particular models using function approximation techniques (i.e. parameter estimation methods such as nonlinear regression methods) (Yadav & Chandel, 2013). Examples of this approach can be found for Madinah (Saudi Arabia) in (Benghanem, 2011), and Singapore in (Zhao, Wang & Goel, 2010), for instance. In (Zhao, Wang & Goel, 2010), the analysis given for modelling from experimental data is based on one year record of solar radiation. Although the method is simple in understanding and applicability, since other meteorological factors are not included in the modelling and solar radiation is a site-specific value, the results is not very accurate but could be used as a starting point for future investigation. In (Benghanem, 2011), the modelling incorporates measurements of air-temperature and relative humidity in addition to solar radiation data for every 5 minutes over the period of 4 years (1998 to 2002). The study however neglected the impact of dust accumulation on solar panels. It also proposed the use of solar trackers for the monthly setting of the tilt angle to the optimum value but the impact of the overall cost of the solar PV system by adding such mechanical systems is not given. Moreover, how the mechanical tracking system will be powered (externally or from the power output of the PV system) and the implication on the overall power output of the solar PV system is also not covered in the study.

In methods of searching for the optimum tilt angles and orientations of solar systems, approaches that include the use of measured data are preferred to those that rely on mathematical models only since weather parameters and other factors (such as the effect of dust) that are peculiar to the particular locations of the systems are included in the search space of the former (Le Roux, 2016). Methods involving the use of mathematical models for specific locations include Lesotho (Gopinathan, 1991), China (Tang & Wu, 2004), India (Suri *et al.*, 2012) and Egypt (Morcos, 1994). Methods based on the use of solar data are available for different locations such as Israel (Manes & Ianetz, 1983), Spain (Bilbao *et al.*, 2003), Hannover (Germany) (Beringer *et al.*, 2011), Subha (Libya) (Nizam *et al.*, 2015) and Tehran (Iran) (Asl-Soleimani, Farhangi & Zabihi, 2001). A comprehensive review on the methods of determining optimum tilt angle is given in (Yadav & Chandel, 2013).

The amount of solar radiation that can be received by a solar PV panel is also determined by its orientation (defined in terms of the azimuth angle). In the northern hemisphere, the orientation is generally towards the south and in the southern hemisphere towards the north. The direction from which the beam and diffuse radiation components reaches a horizontal surface is required to determine the solar radiation on a sloped surface. Factors affecting the value of the diffuse radiation include cloudiness condition and clarity of the atmosphere. The diffuse beam consists of three components: the isotropic part (i.e. uniform solar radiation from the sky dome), the circumsolar part (i.e. part due to the forward scattering of solar radiation), and the (horizon) brightening part (i.e. part due to brightening in clear skies – due to reflection 'albedo' of the ground – and near the horizon) (Yadav & Chandel, 2013) – refer to Figure 3.2.

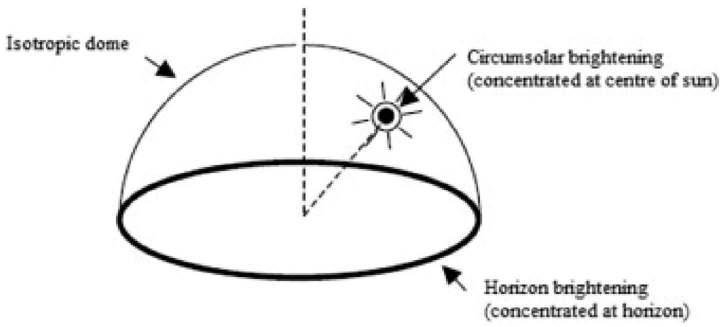


Figure 3.2: An illustration of the three components of the diffuse solar beam (Yadav & Chandel, 2013)

Different optimization techniques have been used to maximize the solar radiation falling on a sloped surface (for solar PV panels and solar thermal collectors alike) in order to compute the optimum tilt and azimuth angles. For a surface tilted at an angle from the horizontal, the optimum tilt angle at any given time is the angle at which the amount of solar radiation that falls on the solar panel is maximum at that time – computed by varying or searching for tilt angle value between 0^{o} and 90^{o}. Search algorithms, or optimization methods, that have been used for determining the optimum tilt angle includes genetic algorithms (Nizam *et al.*, 2015; Talebizadeh, Mehrabian & Abdolzadeh, 2011; Chen, Lee & Wu, 2005), simulated annealing technique and particle swarm optimization method (Chen, Lee & Wu, 2005), artificial neural network techniques (Chang, 2009; Mehleri *et al.*, 2010). Apart from the genetic algorithm, simulated anealing and particle swarm optimization, and the neural network techniques being additional techniques in the toolset of solar PV design engineers, it is not clear why GA should be used instead of standard numerical gradient-descent based nonlinear optimization algorithms for finding optimum tilt or azimuth angles for solar PV systems since the results did not demonstrate better accuracy in finding the optimum tilt angle and/or orientation.

Research is still on-going to find the solution to the challenge of significantly raising the conversion efficiency of PV modules. Once factors that significantly affect the output of a solar PV system that are determined by geographic location and/or installation design (such as latitude, solar insolation, and tilt and azimuth angles) have been appropriately determined or chosen, the influence of other depending factors that can significantly affect the conversion efficiency of solar energy systems arise. One of the most important of these is dust (Mani & Pillai, 2010)**.** Others include bird-droppings, water-stains, and growth of organic species.

3.2.3 Effects of Dust on Solar PV Systems

Dust is a term used to denote small solid particles of diameters less than 500 micro-meter. Various sources of dust occurrence in the atmosphere include, for instance, dust lifted by wind, volcanic eruptions, movement of vehicle or pedestrians. In the context of PV systems' studies, the definition of dust is extended to include small pollens and microfibers that are scattered within the atmosphere and can settle as dust. Dust accumulation on PV systems is influenced by complex phenomena and site-specific weather and environmental conditions. Contamination of optical surfaces by dust and other small particles, also called soiling effect, deteriorates the yield (performance) of solar energy conversion systems due the scattering losses and low absorption of the incident light. Dust settlement is characterised by the dust property (type, size, shape and weight) and the local environment (e.g. nature of prevailing activities around installation area, vegetation type, weather conditions, surface finish of the settling surface, orientation, installation height). Also, as part of the local environment, an initial onset of dust would promote further settlement of dust (i.e. the well-known fact that “dust promotes dust”). Accounting for the effect of gravity and depending on the prevalent wind movements and dust properties, generally horizontal surfaces tend to accumulate more dust than inclined surfaces, and more dust accumulates in low speed wind than in high speed wind. Furthermore, the glazing transmittance decreases due to high deposition of airborne dust and causes degradation of PV efficiency (Mani & Pillai, 2010).

Research studies related to the impact of dust on solar systems include (Garg, 1974) which analysed the influence of dirt on solar transmittance in comparing glass plate and plastic films; it reported a 8% transmittance reduction for a 45^{o} tilted glass plate after just one month. For example, in (Mejia, Kleissl & Bosch, 2014), research on the power output from a PV plant in Santa Clara (CA, USA), found that losses caused due to dust accumulation were around 0.21% per day. Salim, Huraib & Eugenio, (1988) presented results of studies on the long-term dust accumulation on a solar PV system of a village close to Riyadh in KSA; it reported a 32% reduction in performance of the solar array after 8 months in comparison with an identical PV system that was cleaned daily. (Wakim, 1981) presented results of studies on a solar PV system in a Kuwait city; it reported a 17% reduction after 6 days due to sand accumulation on the panel and that there is a greater influence of dust on the system in spring and summer (20% in 6 months) than in the seasons of autumn and winter. However, studies of (Garg, 1974; Salim, Huraib & Eugenio, 1988; Wakim, 1981) have mostly overlooked the speed and direction of the wind, the solar systems orientation, and the properties of the dust of the locations at the time when their research was being carried out. These ignored factors critically determine the extent of dust accumulation and, without their consideration, only generalized statements of conclusions with limited application can be made. Studies that included some of these factors but in an experimental and lab simulation setup include, for instance, (El-Shobokshy & Hussein, 1993b, 1993a; Goossens, Offer & Zangvil, 1993). In (El-Shobokshy & Hussein, 1993b, 1993a), the authors investigate the physical properties of the dust accumulation and the deposition density in relation to PV efficiency; it was reported that finer particles have greater impact on the efficiency than coarser particles. The influence of wind velocity and orientation on the performance of PV systems was studied in (Goossens, Offer & Zangvil, 1993); it was concluded that, generally (neglecting other factors), there is a general increase in dust deposition with increase in wind speed.

In relation to the loss of performance as a function of angle of inclination, the main driver of dust deposition when the solar panel is horizontal (i.e. tilt angle equals 0^o) is gravity – meaning that the soiling rate is proportional to the square of the average diameter of the dust particles. The main driver of dust deposition when the panel is vertical (i.e. tilt angle is 90^o) is diffusion. It should be noted that the accumulation of particles in both cases also depend on, among other factors, the electrostatic charge of the particles. The removal of accumulated dust is also possible by the blowing of the wind; generally, the higher the wind speed and the tilt angle, the higher the rate of removal. Also, the removal rate depends on the average dust diameter and the microstructure of the dust layer – the thinner the layer, the more difficult it is to be removed by wind due to the adhesion force that exists between the particles and the surface (Hinds, 2012). Reduction in transmittance for an area that experiences frequent dust storms, for instance, are 6.28%, 4.62% and 1.87% for 0^o, 45^o and 90^o tilt angle, respectively, for glass specimens cleaned daily and 19.7%, 13.81% and 5.67%, respectively, for glass specimens cleaned weekly, and the loss in transmittance for azimuth angles of 0^o and 90^o are 27.62% and 4.97%, respectively (Nahar & Gupta, 1990).

In relation to the loss of performance as a function of radiation wavelength, it has been found that irrespective of wavelengths that were tested (which varied from 190 to 900 nm), transmittance decreases as the concentration density of dust sample increases. For a given glass sample, the transmittance also decreases as the wavelength increases (Al-Hasan, 1998).

In relation to the loss of performance as a function of environmental parameters such as humidity, wind velocity, and frequency of dust episodes, research has shown that PV systems' efficiency drop when temperature or relative humidity increases (Touati, Al-Hitmi & Bouchech, 2012).

Importantly, in addition to the role of the wind as a soiling agent, the wind also reduces the overall soiling on solar PV systems but it is not very effective for particles smaller than 50 µm. Generally, more dust particles are deposited with increase in velocity of the wind (Cuddihy, 1983; Goossens & Van Kerschaever, 1999). Also, on some PV modules (those made with c-Si solar cells in particular), high wind velocity increases the cell efficiency by reducing the ambient relative humidity (Mekhilef, Saidur & Kamalisarvestani, 2012) and also by cooling the solar panels.

Rain is effective and cheap as a cleansing agent for dust and other pollutants' removal from PV surfaces and there would be no need for regular surface cleansing using alternatives to rain for locations of frequent rainfall that is distributed over the year (Appels *et al.*, 2012; Haeberlin & Graf, 1998; Ryan, Vignola & McDaniels, 1989). However, for occasions where the rain forms sticky muddy layer due to its dust content, immediate cleaning after these events is necessary as muddy layers are detrimental to the performance of the system (AlBusairi & Möller, 2010). Solar PV module surface are also often manually cleaned with tap or distilled water, and sometimes, with detergents (Sayyah, Horenstein & Mazumder, 2014). Brushing after washing has also been found to be effective (Pavan, Mellit & De Pieri, 2011) but excessive scrubbing will sooner or later degrade the performance of the system over time due to the scratches it creates (Freese, 1979).

In order to reduce mainly the cost of labour and minimize water usage while maintaining PV modules' efficiency to acceptable levels, many attempts have been made to automate the procedure of cleaning PV modules by means of control systems techniques and mechanical parts. An example of this is (Tejwani & Solanki, 2010) where a cleaning mechanism is integrated with the tracking system of the solar PV system; however, in this study, the cleaning brushes slide twice over the PV panels twice in any given day and what is missing is the cost of including such mechanism on the PV system and an evaluation of the energy the cleaning and tracking system consumes from the overall PV output. Also, the reduction of the life-span of the PV modules as a result the sliding brushes is not addressed.

Recently, alternative approaches for cleaning PV systems that are devoid of water and manual labour are being proposed; these include the use of electrostatic forces through the use of a so-called electrodynamic screens (Mazumder *et al.*, 2006, 2013), the use of standing-wave electric curtain (Qian, Marshall & Frolik, 2012; Sun *et al.*, 2012) and the exploitation of mechanical vibration principles by using piezo-electric actuators (Williams *et al.*, 2007). These techniques are attractive since they alleviate the problems associated with manual cleaning (such as labour cost, cost of cleaning agents and even water in places where water is not available or scarce). The most promising of all these latest techniques is the transparent electrodynamic screens method. This method requires no water or moving parts and consists of rows of transparent parallel electrodes that are deposited on the front cover glass plates or embedded with a transparent dielectric film of the solar PV panels. The method is capable of removing dust particles within less than 2 minutes using less than 0.1% of the energy produced by the solar system therefore does not require external energy supply. Importantly, the cleaning efficiency of this method is reported to be more than 90% (Mazumder *et al.*, 2013). However, research on the economic justification of using this recently proposed technique that will justify their practical deployment on PV systems in the long term has not been reported and is still an open area of research.

3.3 Equations of Solar Photovoltaic Energy Systems

In this chapter, a possible way of managing electricity peak demand through the deployment of PV panels with slope and orientation optimized in order to improve national electricity generation capacity in a practical way is proposed.

Details of the mathematical model presented in this section can be found in (Duffie & Beckman, 2013; Liu & Jordan, 1961). With the average energy flux S that reaches the top of the Earth's atmosphere from the sun being 1.367 kW/m^2 and which reaches a benchmark value of approximately 1 kW/m^2 for a clear day by the time it reaches a plane surface on Earth, the model given in (Duffie & Beckman, 2013; Liu & Jordan, 1961) is based on the assumption that the total energy flux is equal to the sum of beam (i.e. direct) radiation and the diffuse radiation (as a result of being scattered by clouds and particles), and neglects the effect of the reflected radiation from the environment (that is, components reflected from nearby buildings, trees, roofs, ground, and so on). The model is further described in the following paragraphs.

The declination of the sun δ for any given day n where $n = 1$ on the 1st January is given as follows:

$$\delta = 23.45 \sin\{360(284 + n)/365\} \tag{3.1}$$

Let φ denote the latitude location of a PV system, then the solar sunrise ($-\omega_s$) and sunset (ω_s) times of the day is given as follows:

$$\omega_s = \arccos(-\tan\varphi \tan\delta) \tag{3.2}$$

The sun's elevation ($\sin\alpha$) for each solar hour i of the day can be computed using the following equation:

$$\sin\alpha_i = \sin\delta \sin\varphi + \cos\delta \cos\varphi \cos\omega_i \tag{3.3}$$

where ω_i denotes solar hour angle of the i^{th} hour (the time before solar noon expressed as negative degrees ($-\omega_i$), and the time after solar noon expressed as positive degree (ω_i) and ω_i equals 0^o at solar noon. The solar hour of a given location on the Earth denotes the angle between the longitude of that location and the longitude that is parallel to the beam of the sun at that location (that is, for instance, 0^o, 15^o, 30^o and 45^o represent 12:00 noon, 1:00 pm, 2:00 pm and 3:00 pm, respectively)). The clearness factor d is found from the following equation:

$$\text{s} = s_h \; d \tag{3.4}$$

where s_h is the number of hours between sunrise and sunset and s the number of sunshine hours observed or predicted for the day from meteorological data. The clearness index for the day is given by the following equation (Duffie & Beckman, 2013):

$$K = e_c \sqrt[3]{d} \tag{3.5}$$

where e_c is an empirical constant defined as e_c= 0.65 if $\varphi > 45^o$ or e_c= 0.75 if $\varphi \leq 45^o$. The solar beam energy and solar diffuse energy, denoted B and D respectively, are given by the following empirical equations (Duffie & Beckman, 2013):

$$B = 1.11\ H_o\ K^2 \tag{3.6}$$

$$D = H_o\ K - B \tag{3.7}$$

where H_o is the extra-terrestrial energy directed to a unit horizontal area over a given day and location, and can be approximated as:

$$H_o = \sum_{i=1}^{i=N} 1.367\ \sin \alpha_i \tag{3.8}$$

where N is the number of integer hours of daylight. Therefore, the total energy (in kW) that can be generated by a PV plant of X (in kWp) capacity and inverter efficiency of η (in %) on a particular day can be written as follows:

$$E_T = \sum_{i=1}^{i=24} \eta \times X\ \times\ \sin \alpha_i\ \times G_i \tag{3.9}$$

where $E_T =$ Total energy generated by the plant in a day and, in Equation 3.9, the value of $\eta \times X \times \sin \alpha_i\ \times G_i$ is zero outside the daylight hours (e.g. for $i = 1$ to 9 and for i =19 to 24).

$$G_i = B\ r_{b_i} + D\ r_d \tag{3.10}$$

$$r_{b_i} = \frac{\cos\ (\varphi-\beta) \cos \delta \cos(\omega_i - z\ \sin \beta) + \sin(\varphi-\beta) \sin \delta}{\cos \varphi \cos \delta \cos \omega_i + \sin \varphi \sin \delta} \tag{3.11}$$

$$r_d = \frac{1}{2}(1 + \cos \beta) \tag{3.12}$$

where β is the tilt angle (that is, the angle between the plane of the PV panel surface and horizontal) which when positive means that the surface orientation is towards the equator and when negative means the surface is towards the pole, z is the azimuth angle, r_b and r_d are known as the panel angle incident beam radiation and panel angle incident diffuse radiation factors, respectively.

It should be noted the output of PV solar panels are commonly given in terms of their performance at a given ambient temperature; thus, to account for the effect of temperature on the efficiency of PV systems, using as an example the Sharp® ND-R250A5 polycrystalline silicon photovoltaic modules that have temperature coefficient $\epsilon = -0.0044°\mathrm{C}^{-1}$ with the standard test condition temperature being 25°C (Sharp-Electronics-Website, 2011) are used, the factor $\left(1 + \epsilon(T_a - 25)\right)$ can be multiplied to the expression on the right of Equation (3.9) to give the following:

$$E_T = \sum_{i=1}^{i=24} \eta \times X \times \sin\alpha_i \times G_i \times \left(1 + \epsilon(T_a - 25)\right) \quad (3.13)$$

where T_a is the ambient temperature profile that could be averaged over a given period of time, for instance, over a day's sunshine hours, a month and so on, depending on the context.

3.4 Harvestable Solar Radiation for Solar PV Generating Systems in Riyadh City Using Roofs of Malls, Mosques, and Schools

In KSA, because electricity companies are mostly owned by the government, existing roofs of malls, mosques and schools in the city of Riyadh – which are all government owned – can be exploited by using them for solar panel installation. In this section, we will make an attempt to estimate the area that is available for this installation. This estimate will be used in the next section, in combination with a calculation of the optimal tilt and azimuth angles for the solar panels, to determine the energy output that will match the timing and profile of peak load with consideration of the effect of weather and dust accumulation.

Table 3.1 lists the names and sizes of roofs and parking areas of all the malls that have a total area greater than 2000 m^2 in the city of Riyadh. Google Earth has been used to obtain values on the table. In general, the combined total area of the malls is 2,395,000 m^2.

In practice, not all the total roof areas of these malls can be used for solar panel installation; for convenience in this analysis, it will be assumed that only 50% of the available total roof size of each of these malls will be used for solar panel installation. Accordingly, the combined total roof areas of the malls that will be used for solar panel installation is 1,197,500 m^2.

Table 3.1: List of names and sizes of roofs and parking areas of the big malls with a total area greater than 2000 m² in the city of Riyadh

	Name of Mall	Roof Area (m2)	Parking Area (m2)	Total Area (m2)
1	Akaria Malls (1,2,3 and Plaza)	53,000	7,600	60,000
2	AL Ageeg Square	6,000	0	6,000
3	AL Humra Plaza	39,000	10,000	49,000
4	AL Khaleej Mall	34,000	0	34,000
5	Al Muaigliah Mall	38,000	20,000	58,000
6	Al Nakheel Mall	6800,000	7,671	75,000
7	Al Orobah	56,000	12,000	68,000
8	AL Othaim Mall (eastern ring)	39,500	26,600	65,000
9	AL Othaim Mall (Khuris rd.)	27,700	19,000	46,000
10	Al Qasr Mall	31,000	0	31,000
11	AL Qudis Market	16,000	12,000	28,000
12	AL Shoalah Center	15,000	0	15,000
13	AL_Riyadh Mall	25,000	18,000	43,000
14	Riyadh National shopping centre	23,000	7000	30,000
15	AL-Haram Mall	8,000	5,000	13,000
16	AL-Jazerah Shopping Centre	9,000	7,000	16,000
17	Almakan Mall	15,000	7600	22,600
18	Alodah Mall	12,000	0	12,000
19	Alowais Mall	80,000	0	80,000
20	Alshifa Mall	12,000	3,000	15,000
21	AL-Yasameen Mall	16,000	18,000	34,000
22	Ar Riyadh ALdouli Market	27,000	6,000	33,000
23	Arcade Center	6,000	0	6,000
24	Batha Commercial Centre	8,000	0	8,000
25	Billy Beez	23,000	20,000	43,000
26	Carrefour (Khrais)	6,000	14,000	20,000
27	Carrefour AL-Suwaidi	35,000	8,000	43,000
28	Granada centre	61,000	200,000	260,000
29	Hayah Mall	66,000	50,000	116,000
30	Home market (across IKEA)	2000	0	2,000
31	Khorais Mall	35,000	11,000	46,000
32	Localizer Mall	14,000	8,000	22,000
33	LuLu Market (Khorais)	10,000	1,000	11,000
34	Marina Mall	19,000	3,000	22,000
35	Nesto Hypermarket Bataha	9,000	0	9,000
36	Nojoud Mall	8,000	0	8,000
37	Panorama Mall	48,000	22,000	70,000
38	Rimal Centre (IKEA)	190,000	110,000	300,000
39	Riyadh Gallery mall	56,000	50,000	100,000
40	Riyadh Outlet mall	30,000	36,000	66,000
41	Riyadh Park	60,000	20,000	80,000
42	Royal Mall	15,000	3,500	15,000
43	Sahari Mall	52,000	27,000	78,000
44	Salaam Mall	41,000	30,000	71,000
45	Shari Plaza	7,000	2,400	8,000
46	Sultanah Plaza	20,000	20,000	40,000
47	Tafaseel park	6,000	0	6,000
48	Tala Mall (Northern Ring)	23,000	11,000	34,000
49	Taybah Mall	45,000	20,000	65,000
50	Ten City Mall	10,000	7,000	17,000
51	Venicia Mall	16,000	2,000	18,000
Total				**2,395,000**

As at 2009, there are 2,243 and 8,103 “big” and “small” mosques (a total of 10,346), respectively, according to official record. By 2017, the total number has increased to 18,073 (an increase of 75%). Being big or small is determined, not by size but, by whether or not Friday congregational prayers are held in the mosque or not. These mosques all have different sizes from the biggest, the King Khalid Mosque, of 21,000 m^2 in size to one of the smallest of the big mosques, the Al-Rajhi Grand mosque of 1,600 m^2. Table 3.2 lists the names and sizes of six of some of the most popular mosques in the city of Riyadh.

Table 3.2: List of some of the most popular mosques in the city of Riyadh

Name of Mosque	Area (m^2)
King Khalid Mosque	21,000
Al-Rajhi Mosque	11,000
Princess Latifa bint Sultan	8,000
Fahad Al-Owaidah Mosque	5,000
Olaya Compound Mosque	4,000
Al-Rajhi Grand Mosque	1,600

Practically, not all the total roof areas of these mosques can be used for solar panel installation; some areas are covered by domes, some areas are covered mostly by shadows, and so on. Thus, for convenience, it will be assumed that only 500 m^{2}of the total roof size of each of the 18,073 mosques in the Riyadh region will be used for solar panel installation. It should be noted that, although, there is no data on the specific dimensions of the mosques in KSA, the sizes of the mosques (which includes the praying areas for the men and women, for ablution, for parking and usually other rooms) must not be less than 750 m^2 (Moia, 2017) and, for comparison, are larger than the sizes of residential houses which are 625 m^2 on the average (MOMRA-Website, 2017). This makes of the assumption of taking only 500 m^2 of the roofs and parking areas of the mosques reasonable although many of the mosques have much larger roof areas Accordingly, the combined total roof areas of the mosques that can be used for solar panel installation is 9,036,500 m^2.

Also, the total numbers of boys’ and girls’ government schools in Riyadh are 1151 and 1351, respectively (a total of 2,522). The roof area of each of these schools vary but is greater than 1000 m^2 (if the parking area is excluded) and, in general, the land areas of all the schools range from the minimum of 2000 m^2 to a maximum of 3000 m^2. For convenience again, we will assume that the roof area of each of the schools that is suitable for PV panel installation is 1000 m^2. This author recognizes that it would have been more useful to use the weighted average of all the schools to arrive at a fraction that can be used for PV panel installation; however, data on the exact sizes of these schools that would make that possible is not available at the time of carrying out this research. Accordingly, the combined total roof areas of the schools that can be used for solar panel installation is 2,522,000 m^2.

The combined total roof areas of the malls, mosques and schools that can be used for PV panel installation, therefore, is 12,756,000 m^2. A typical size of a solar panel is 1.6 m^2; thus, $12{,}756{,}000/1.6 = 7{,}972{,}500$ number of solar panels will be required to fill these spaces; assuming that this number of solar panels are actually installed on the roofs of total size of 12,756,000 m^2 and each solar panel has a rated capacity of 300 Wp (which is the typical value; see, for example, (Sharp-Electronics-Website, 2018)), the total output peak power that can be generated from these solar panels is $7{,}972{,}500 \times 300$ Wp = 2,391,750 Wp or approximately 2.4 GWp.

3.5 Algorithm for Optimal Tilt and Azimuth Angles

Consider the problem of finding the optimal tilt angle β and azimuth angle z that gives the maximum solar energy from a set of PV generation plants in the region of Riyadh with total capacity of 2.4 GWp and inverter efficiency of 98% (Team *et al.*, 2005; Burger & Kranzer, 2009), given that it is known that the peak demand for electric power in KSA occurs between 12:00 and 17:00 in summer months, the algorithm to find the optimum β and azimuth angle z takes into account the shape of the demand profile (refer to Figure 1.2) by matching the peak demand time with the time of the day when solar energy generation is maximum.

The algorithm is given as follows:

STEP 1: Create a vector of 24 elements – each element being the solar hour angle for each hour of the day.

STEP 2: Create a new vector by shifting each elements of the vector created in *STEP 1* in order to make the maximum output of PV to match the peak demand time.

STEP 3: For $n = 1$ to $n = 365$

STEP 4: Compute δ using the Equation (3.1)

STEP 5: Compute solar hour angle ω_s for sunrise and sunset using the Equation (3.2)

STEP 6: Compute the solar elevation ($\sin \alpha$) for each solar hour i of the day using Equation (3.3)

STEP 7: Set the solar elevation ($\sin \alpha$) for each solar hour i of the day outside the daylight hours to zero (daylight hours are the hours between the solar hour angle for sunrise and sunset inclusive).

STEP 8: Compute d – the clearness factor for the day – using the Equation (3.4)

STEP 9: Compute the clearness index K for the day using the Equation (3.5)

STEP 10: Compute the solar beam energy B and the solar diffuse energy D using Equations (3.6) and (3.7), respectively.

STEP 11: Find the optimum β and z for the day by maximizing the total energy generated on the day using Equation (3.13); the total energy generated on any given day for this can be computed using equation (3.14):

$$E_T = \sum_{i=1}^{i=24} 0.98 \times 2400000 \times \sin \alpha_i \times G_i \times \left(1 + \epsilon(T_a - 25)\right) \tag{3.14}$$

3.5.1 Numerical Results

MATLAB software can be used to implement the algorithm given in Section 3.5. In particular, MATLAB's nonlinear constrained optimization algorithm *fmincon* can be used for solving the optimization problem (refer to Appendix A). The optimization (maximization) problem of the power generation over a day of the set of PV plants of total capacity of 2.4 GWp and inverters' efficiency of 98% (Team *et al.*, 2005) can be written as equation (3.15):

$$\underset{\beta,z}{\text{Minimize}} \ -\sum_{i=1}^{i=24} 0.98 \times 2400000 \times \sin \alpha_i \times G_i \times \left(1 + \epsilon(T_a - 25)\right) \tag{3.15}$$

Figure 3.3 shows the typical nature of weather in Riyadh over the months of the year. The climate of the city of Riyadh (latitude 24.63°, longitude = 46.67°) is typical of the entire

Arabian peninsula which experiences mean cloud cover under 15% with a near-0% cloud cover centred on Riyadh (Mott & Sheldon, 2000). Table 3.3 (a) gives the normalized daily sunshine data for the city of Riyadh for each month and Table 3.3 (b) gives the averages of the monthly temperature (with the low and high average temperatures denoting the statistical average of the low and the high monthly temperatures taken over the period of 30 years). The 'Average High Temperature' will be used in the computation that follows given that it is more representative of the temperature during the day's sunshine hours when the PV panels will be put to use. Incorporating the normalized daily sunshine data of Table 3.3 and Table 3.4 into the algorithm given in Section 3.5 (that is, the clearness index (K) for all the days of January being 7/11, all the days of February being 8/11, all days of March being 7/11, and so on, and the ambient temperature for all the days of January being 19°C, all the days of February being 22°C, all days of March being 26°C, and so on), the optimum average monthly tilt and azimuth angles are shown in Figure 3.4 and Table 3.5.

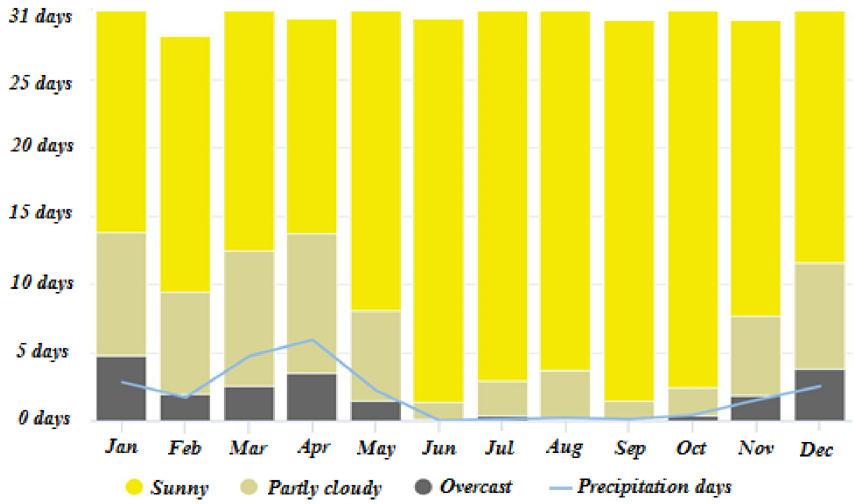


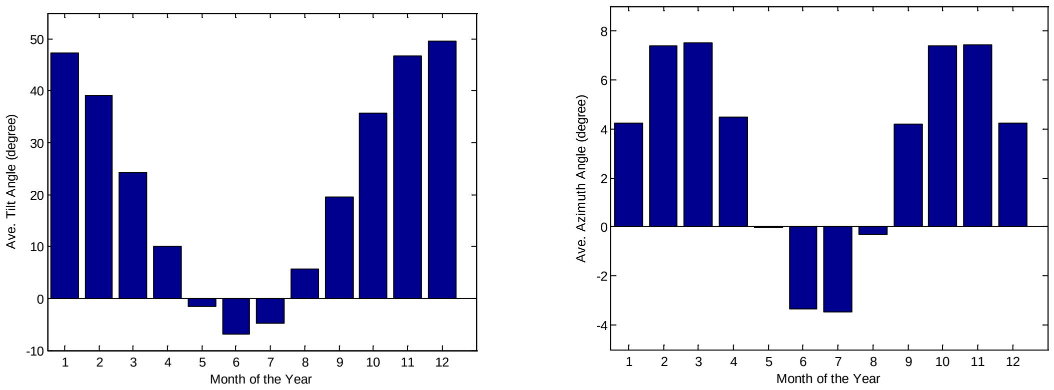
Figure 3.3: Cloudy, sunny, and precipitation days (Meteoblue-Website, 2017)

Table 3.3: Riyadh City's Average Daily Sunshine (Weatherbase-Website, 2018)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Daily Sunshine hours	7	8	7	8	9	11	11	10	9	10	9	7

Table 3.4: Riyadh City's Monthly Temperature Averages (Weatherbase-Website, 2018)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Temperature (°C)	14	16	21	26	32	34	36	35	32	27	21	16
Average High Temperature (°C)	19	22	26	32	38	41	42	42	40	34	27	21
Average Low Temperature (°C)	8	11	15	15	20	25	27	28	28	25	20	15



(a) (b)

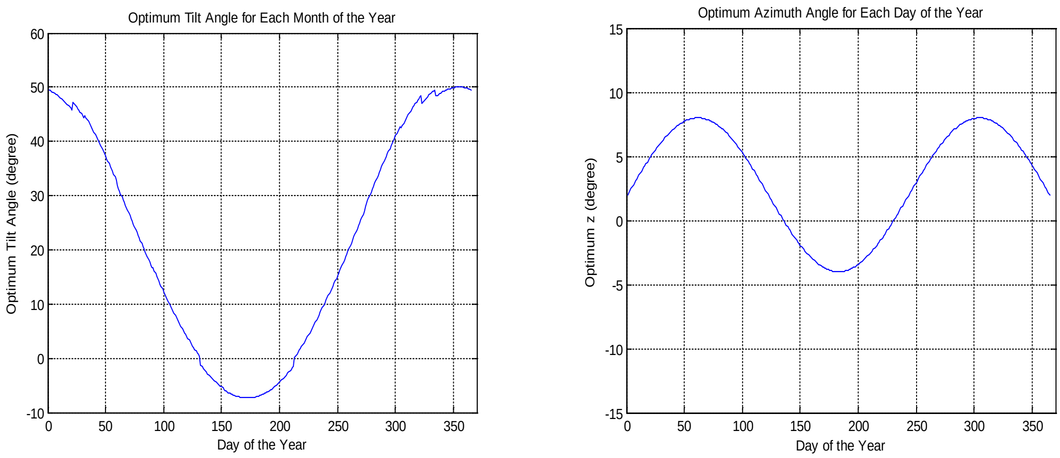
Figure 3.4: Riyadh City's Optimum Monthly Tilt and Azimuth Angles, (a) and (b), respectively.

Table 3.5: Riyadh City's Optimum Monthly Average Tilt and Azimuth Angles

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Optimum Tilt Angle	47.3	39.2	24.2	10	-1.6	-7	-5	5.7	19.6	35.6	46.8	49.6
Average Optimum Azimuth Angle	4.2	7.4	7.5	4.5	-0.02	-3	-4	-0.3	4.2	7.4	7.4	4.2

In relation to the implementation of the algorithm, the optimum tilt and azimuth angles are those for which the maximum PV generation and the actual demand maximum occur at the same time so that distributed PV generation around the city mitigates the challenging peak demand seen by the large scale conventional power plants. Therefore, from Figure 1.2, the time at which the typical daily load curve peaks during the summer months is 14hr 22 minutes; the peak of the unmatched PV generation daily curve is at 12 noon - meaning that the matching ('shift') angle is 2 hr 22 minutes or 35.43^{o} in solar hour and this has value has been used to obtain our results. The plot of the optimal tilt and azimuth angles computed for each day of the year using the algorithm with sunshine hours for Riyadh matched at 35.43^{o} is shown in Figure 3.5.

Figure 3.6 shows the solar energy generation of the plant for each day of the year where the obtained optimum values of tilt and azimuth angles are used for computing the daily plant electricity generation. The results show that the maximum daily power electricity generation in during the year is 2,214 MW and the tilt and azimuth angles at which that occurred are -5.79° and -2.17°, respectively, which is on the 152nd day of the year (that is, beginning of June), Because Riyadh has a tropical location, the sun's path moves from a southern to northern orientation in summer resulting in a negative value for tilt.



(a) (b)

Figure 3.5: Optimum Tilt and Azimuth Angles for Each Day of the Year for Riyadh City

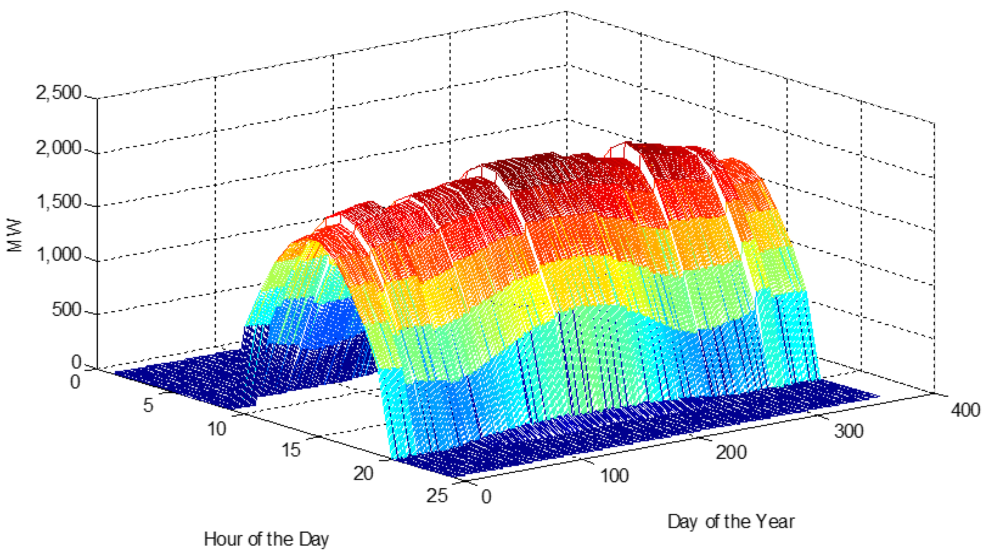


Figure 3.6: A Mesh of PV Generation of a Plant in Riyadh City with Capacity of 2400 MWp computed for the Whole Year Using Daily Optimum Values of Tilt and Azimuth Angles

Figure 3.7 shows the plot of the daily solar plant electricity generation computed for the whole year with a fixed tilt angle of 2.36° and azimuth angle of -0.6° which are obtained by taking the average values of the optimum angles for five summer months (May to September); this solar plant generated its maximum power of 2,233 MW on the 158th day of the year. It should be noted that the value of the maximum power generated using the optimum angles for five summer months here is higher than that for the power generated during with the optimum angles from daily optimum; this is due to the fact that the optimization algorithm considered that average of the monthly weather parameters in both cases (rather than, for example, considering daily weather parameters). It is also for the same reason that there is discontinuity in the figures.

Figure 3.8 shows the plot of the daily solar plant electricity generation computed for the whole year when the tilt and azimuth angles are fixed to the values of 36.12° and 6.06°, respectively, which are obtained by taking the average values of the optimum angles for the seven winter months (October to April); this solar plant generated its maximum energy of 2,137 MW on the 277th day of the year.

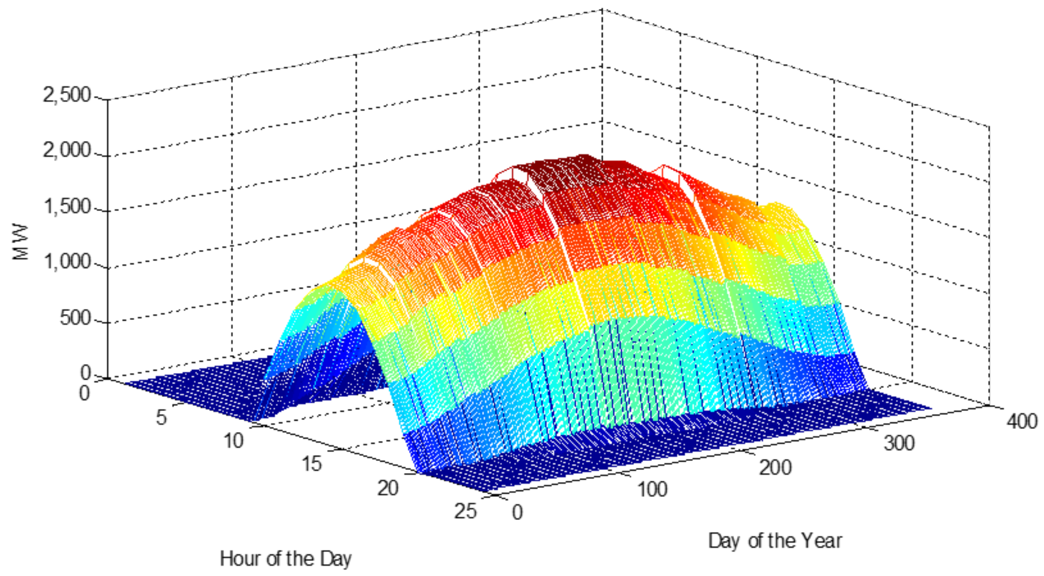


Figure 3.7: A Mesh of the Daily Solar Plant Electricity Generation computed for the Whole Year with a Fixed Tilt Angle of 2.36° and azimuth angle of -0.6°

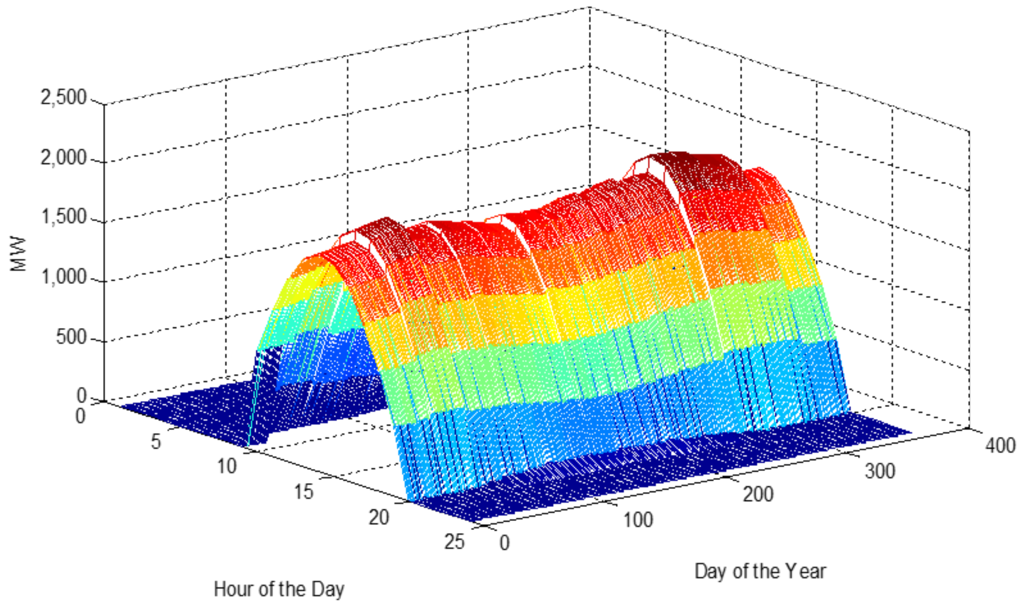


Figure 3.8: A Mesh of the Daily Solar Plant Electricity Generation computed for the Whole Year with Fixed Tilt and Azimuth Angles of 36.12º and 6.06º, respectively

Figure 3.9 shows the plot of the maximum energy generated for each day of the year computed using optimum value of β for each month as well as various fixed values of β (i.e. β set to the average daily optimum β of five summer months (May to September), which are considered to be summer due to the climate in KSA, β set to the average daily optimum β of the other seven non-summer months, (October to April), and β set to the value for which yearly maximum energy is obtained) for the whole year. It is important to note that the summer months in KSA can be more than five months (generally from April to October) but the author preferred to stick to official definition of summer months according to ECRA.

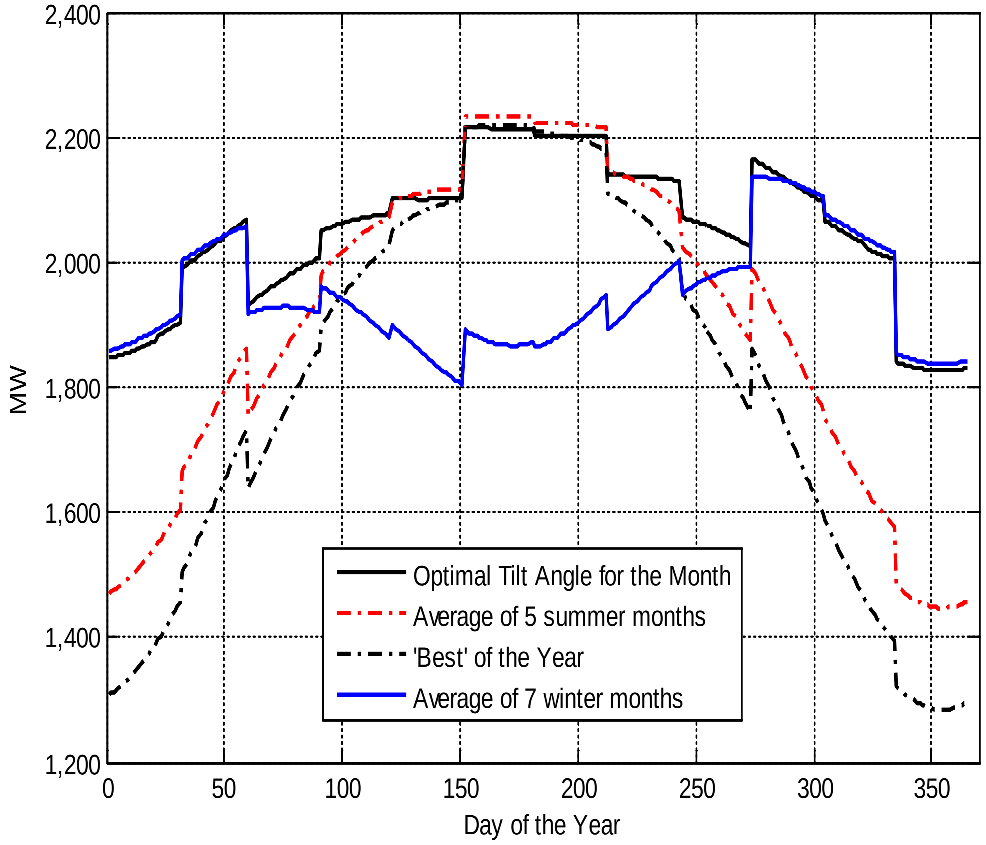


Figure 3.9: Maximum PV Plant Generation with Different β Values for the Whole Year

The total installed generation capacity of KSA is around 54 GW and the generation units are distributed throughout the major cities. In particular, the typical summer peak load demand for the city of Riyadh was 20.349 GW in 2015 (ECRA, 2015). The associated load curves for the matched and unmatched cases when the set of PV generation units of 2.4 GWp capacity that we have considered so far in this section is installed to supplement the energy demand in that city are shown in Figure 3.10.

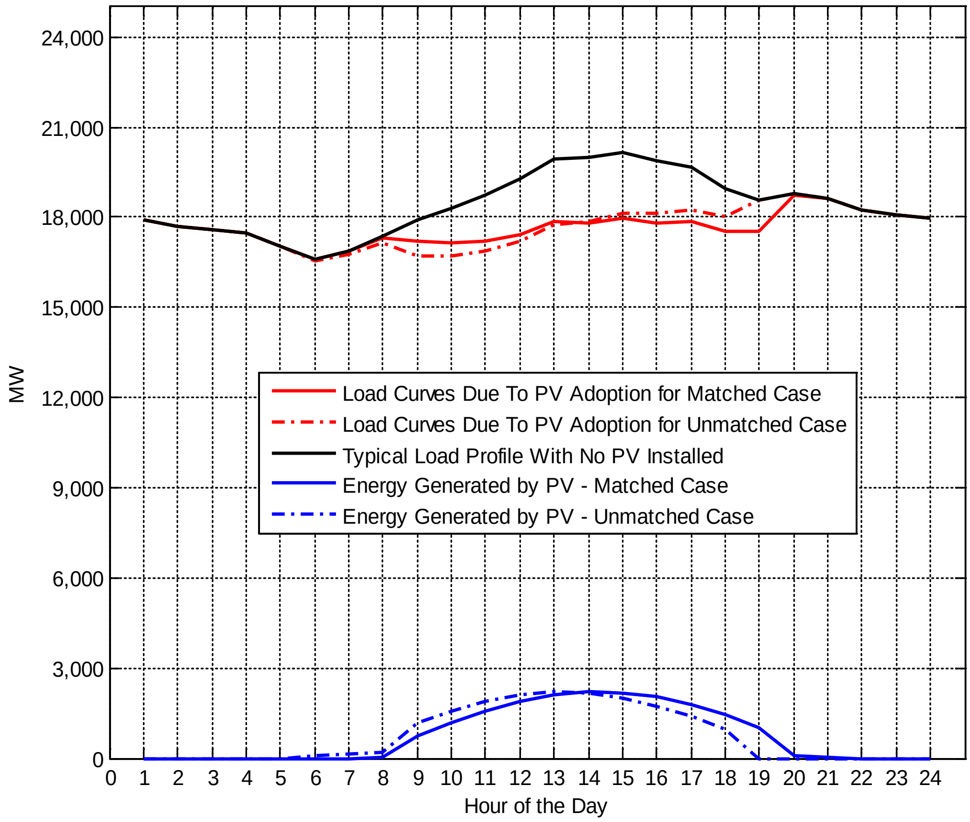


Figure 3.10: The load curves on the 195th day of the year for the matched and unmatched cases when the PV generation unit is adopted for electricity generation in the city of Riyadh.

3.6 Considering the Effects of Dust Accumulation for Optimal Tilt and Azimuth Angles

A trial study was conducted by (Elminir *et al.*, 2006) in Cairo, Egypt, to investigate the effect of dust on solar PV systems measuring the transmittance of light radiation through glass plates that were set at various angles and cleaned monthly. From that study, taking the average values of the data (from December 2004 to June 2005 with the surfaces wiped clean monthly for the location lat. /long.: 29°52′, 31°20′ in Cairo, Egypt) on the average monthly reduction in normal transmittance with respect to tilt angle and direction given in Table 3.6 is obtained.

Table 3.6: Average monthly reduction in normal transmittance with respect to tilt angle

Tilt Angle, β	0°	15°	30°	45°	60°	75°	90°
Average Reduction in Normal Transmittance L (L, [%])	27.62%	20.18%	18.47%	15.96%	13.62%	10.82%	6.32%

Using the polynomial regression method, a third order polynomial model for the relationship in Table 3.6 can be written as follows:

$$L = c_0 + \beta c_1 + \beta^2 c_2 + \beta^3 c_3 \tag{3.16}$$

where $c_0 = 0.27$, $c_1 = -0.005163$, $c_2 = 8.38 \times 10^{-5}$, and $c_3 = -5.8 \times 10^{-7}$. The fitness plot is shown in Figure 3.11. The use of a third order polynomial model has been adopted as the second order model, which is almost a linear line, It does not capture the nonlinear relationship; likewise, a higher order model (for example, a fourth order polynomial or higher) leads to overfitting of the model.

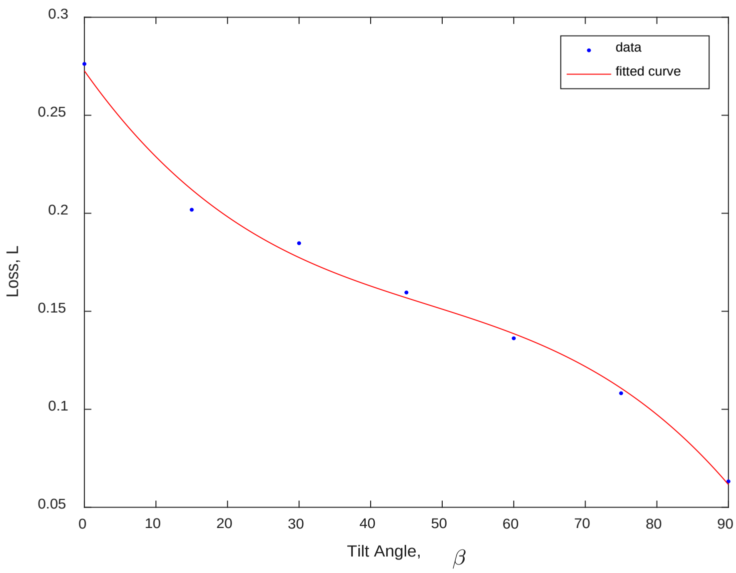
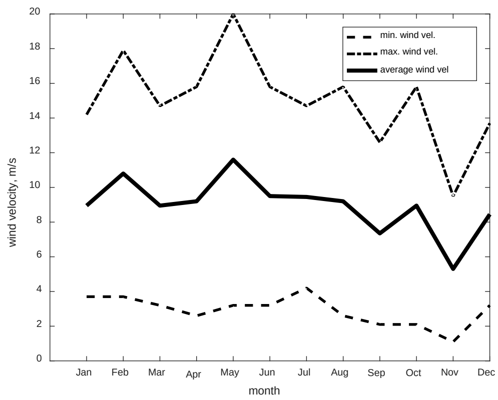


Figure 3.11: Fitness plot for the average monthly reduction in normal transmittance with respect to tilt angle obtained using the polynomial regression method

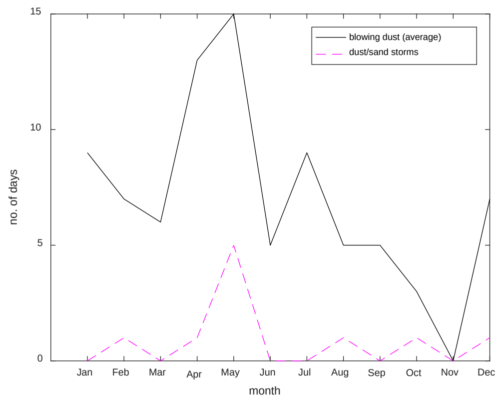
According to (Notaro *et al.*, 2013), the dust storms occur mainly from February to June. In general, Riyadh has dry weather between June and October while there is intermittent rain in April. For a typical year, the monthly values of wind velocity, mean number of days of blowing dust and the number of days of a typical dust/sand storm (i.e. days with visibility less than 1.6 km) is given for Riyadh city in Table 3.7 and Figure 3.12 (Modaihsh, 1997).

Table 3.7: The monthly values of wind velocity, mean number of days of blowing dust and the number of days of a typical dust/sand storm for Riyadh city

Month	Wind Velocity (m/s)			Dust/sand storms (no. of days)	Blowing dust (mean no. of days)	Blowing dust weighted difference (Actual days 'minus' Mean days) adjustment to c_0 Weight = 0. 008; Mean = 7
	Min.	Max.	Average			
Jan	3.7	14.2	8.95	0	9	0.016
Feb	3.7	17.9	10.80	1	7	0
Mar	3.2	14.7	8.95	0	6	-0.008
Apr	2.6	15.8	9.20	1	13	0.048
May	3.2	20.0	11.60	5	15	0.064
Jun	3.2	15.8	9.50	0	5	-0.016
Jul	4.2	14.7	9.45	0	9	0.016
Aug	2.6	15.8	9.20	1	5	-0.016
Sep	2.1	12.6	7.35	0	5	-0.016
Oct	2.1	15.8	8.95	1	3	-0.032
Nov	1.1	9.5	5.30	0	0	-0.056
Dec	3.2	13.7	8.45	1	7	0
Mean	2.9083	15.0417	8.9750	0.8333	7	0



(a)



(b)

Figure 3.12: (a) Monthly variation of minimum, maximum and average wind velocities, and (b) average number of days of blowing dust and number of days of a typical dust/sand storm, for a typical year

Assuming that the average monthly transmittance reduction data of Table 3.6 taken for Egypt is representative of the average monthly transmittance reduction data of Riyadh city, it is clear from Table 3.7 and Figure 3.12 that average monthly reduction curve can differ from the actual monthly loss-tilt angle curve over a wide range depending on the month. To take into account the variation of the reduction curve for each month, assuming that the shape of the curve in Figure 3.11 (i.e. the balance between dust accumulation and removal) is preserved for each month but the location of the curve (‘shift’ along the y-axis – which signifies the density of dust deposition) varies depending on the weighted difference between the actual and the mean number of days of blowing dust (refer to the last column of Table 3.7). The use of the weighted difference between the actual and the mean number of days of blowing dust is meant to capture the deviation from the average value.

It should be noted that the assumption that the rate of dust accumulation and removal is preserved for each month is not entirely true since it would be expected that there will be less accumulation of dust in rainy seasons due to the cleansing effect of rain water ((AlBusairi & Möller, 2010) – also refer to (Sayyah, Horenstein & Mazumder, 2014), for instance, for an example on monthly variation of the loss-tilt angle curve). Also, the weight is chosen (in this case as 0.008) so that the maximum loss for a monthly cleaned solar PV panel’s surface on the month with highest number of days with blowing dust (i.e. May) is below 34% at a tilt angle of 0^o and the maximum loss for a monthly cleaned solar PV panel’s surface on the month with lowest number of days with blowing dust (i.e. November) is above 21% at a tilt angle of 0^o. Here, the choice of the ‘34%’ is based on the report in (Salim, Huraib & Eugenio, 1988) that there is a 32% reduction in performance of the solar PV system of a village close to Riyadh in KSA after 8 months in comparison with an identical PV system that was cleaned daily. And also, the choice of the ‘21%’ is based on the report for a city in Kuwait (which, due its location and climate, it can safely be assumed that it is similar to that of Riyadh) given in (Wakim, 1981) that dust influence can cause a loss of 20% in the spring and summer months more than in the autumn and winter months for un-cleaned solar PV panels for 6 months. Of course, these choices of ‘34%’ and ‘21%’ is made for simplicity. It should be noted that Egypt, Kuwait and KSA have approximately equal monthly average wind speed (NASA, 2018) and, generally, there is an increase in dust deposition with increase in wind speed (Goossens, Offer & Zangvil, 1993). With these factors in mind, it is understood that the 32% and 21% reduction in the performance of solar PV systems are based on the 8 months and 6 months data (a discrepancy of 2 months), respectively, the author believes that this is the best estimation possible in the absence of any other data on this subject. The proposed shift of the loss-tilt angle curve is equivalent to addition of entries of the right-most column of Table 3.7 to the already obtained value of $c_0 = 0.27$; this gives the new value of c_0 for each month as shown in Table 3.8. The corresponding loss-tilt angle curve for each month is given in Figure 3.13.

Table 3.8: The value of c_0 for each month of the year for Table 3.7

Month	Average Wind Velocity (m/s)	Blowing dust (mean no. of days)	Blowing dust weighted difference (Actual 'minus' Mean) Weight = 0.008; Mean = 7	Model: $L = c_0 + \beta c_1 + \beta^2 c_2 + \beta^3 c_3$ $c_1 = -0.005163$, $c_2 = 8.38 \times 10^{-5}$, $c_3 = -5.831 \times 10^{-7}$ [Old value of $c_0 = 0.27$] New value of c_0
Jan	8.95	9	0.016	0.29
Feb	10.80	7	0	0.27
Mar	8.95	6	-0.008	0.26
Apr	9.20	13	0.048	0.32
May	11.60	15	0.064	0.34
Jun	9.50	5	-0.016	0.26
Jul	9.45	9	0.016	0.29
Aug	9.20	5	-0.016	0.26
Sep	7.35	5	-0.016	0.26
Oct	8.95	3	-0.032	0.24
Nov	5.30	0	-0.056	0.22
Dec	8.45	7	0	0.28

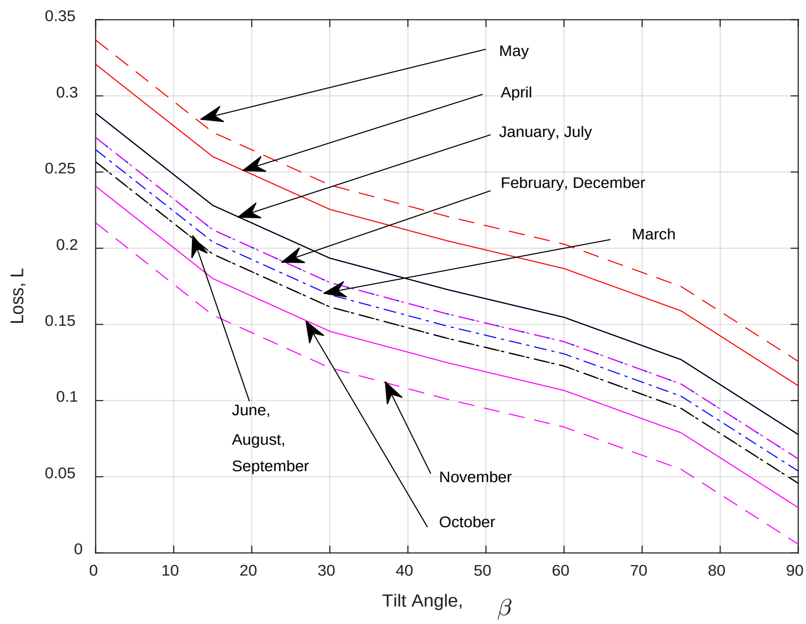


Figure 3.13: The loss-tilt angle curve for each month of the year

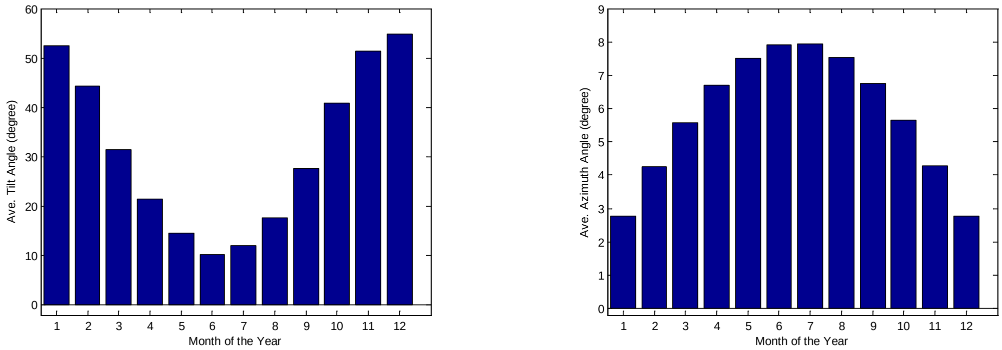
Incorporating the effect of dust into the algorithm of Section 3.5, the total energy generated on any given day of STEP 11 can now be written as follows:

$$E_T = \sum_{i=1}^{i=24} 0.98 \times 2400000 \times \sin \alpha_i \times G_i \times \left(1 + \epsilon(T_a - 25)\right) \times (1 - L)$$

where $L = c_0 + \beta c_1 + \beta^2 c_2 + \beta^3 c_3$. Consequently, the optimization (maximization) problem of the power generation over a day of the set of PV plants under consideration can now be written as follows:

$$\underset{\beta,z}{\text{Minimize}} \quad -\sum_{i=1}^{i=24} 0.98 \times 2400000 \times \sin \alpha_i \times G_i \times \left(1 + \epsilon(T_a - 25)\right) \times (1 - L)$$

The optimum average monthly tilt and azimuth angles are shown in Figure 3.14 and Table 3.9.



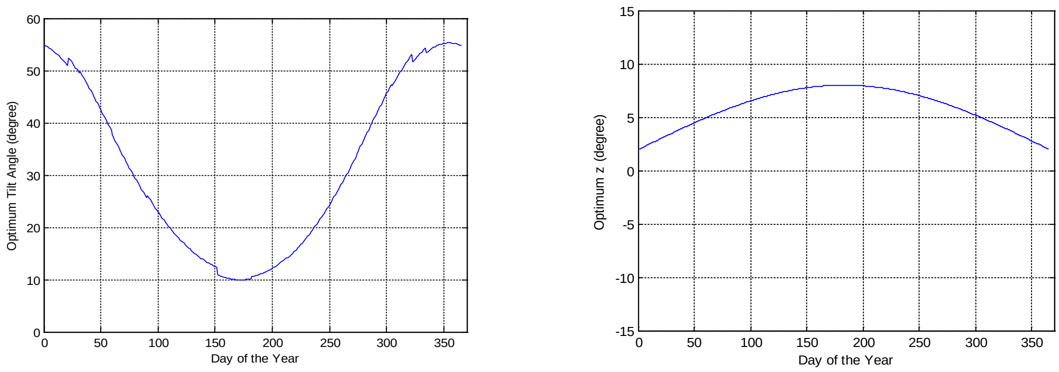
(a) **(b)**

Figure 3.14: Riyadh City's Optimum Monthly Tilt and Azimuth Angles with the Consideration of the Average Monthly Dust Accumulation, (a) and (b), respectively.

Table 3.9: Riyadh City's Average Optimum Tilt and Azimuth Angles with the Consideration of the Average Monthly Dust Accumulation

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Optimum Tilt Angle	52.4	44.3	31.5	21.4	14.5	10.2	12	17.7	27.7	40.8	51.4	54.8
Average Optimum Azimuth Angle	2.8	4.2	5.6	6.7	7.5	7.9	7.9	7.5	6.8	5.7	4.3	2.8

The plot of the optimal tilt and azimuth angles computed for each day of the year after taking into account the effect of dust accumulation and with sunshine hours for Riyadh matched at 35.43^{o} is shown in Figure 3.15. The results show that the maximum power generation in the year is 1,850 MW (as against 2,233 MW when dust was not considered) and the tilt and azimuth angles at which that occurred are 34.11° and 6.24°, respectively, which is on the 274th day of the year (that is, 1st day of October). Figure 3.16 shows the solar energy generation of the plant for each day of the year where the obtained optimum values of tilt and azimuth angles are used for computing the daily plant electricity generation.



(a) (b)

Figure 3.15: Optimum Tilt and Azimuth Angles for Each Day of the Year for Riyadh City with the Consideration of the Average Monthly Dust Accumulation

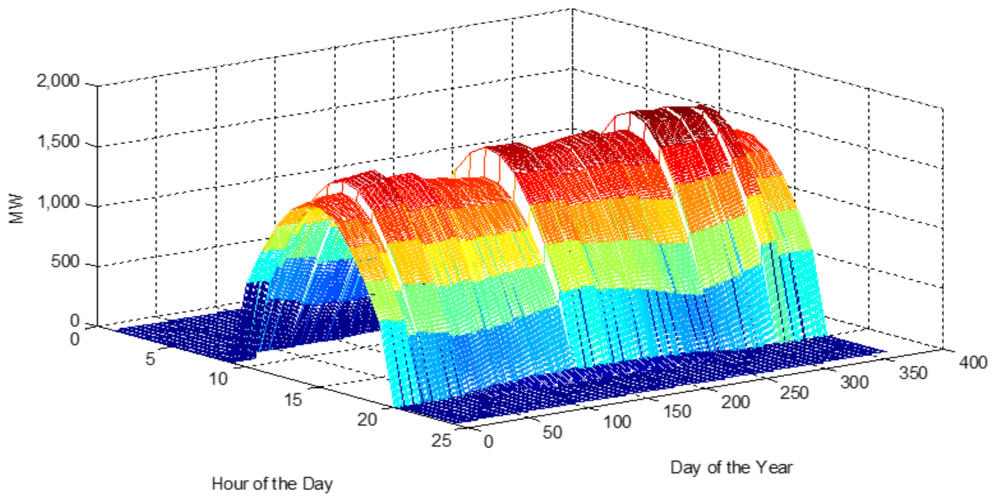


Figure 3.16: A Mesh of PV Generation of a Plant in Riyadh for the Whole Year Using Daily Optimum Values of Tilt and Azimuth Angles with the Consideration of the Average Monthly Dust Accumulation

Figure 3.17 shows the plot of the daily solar plant electricity generation computed for the whole year with a fixed tilt angle of 16.38° and azimuth angle of 7.53° which are obtained by taking the average values of the angles for five summer months (May to September); this solar plant generated its maximum energy of 1,891 MW on the 152nd day of the year.

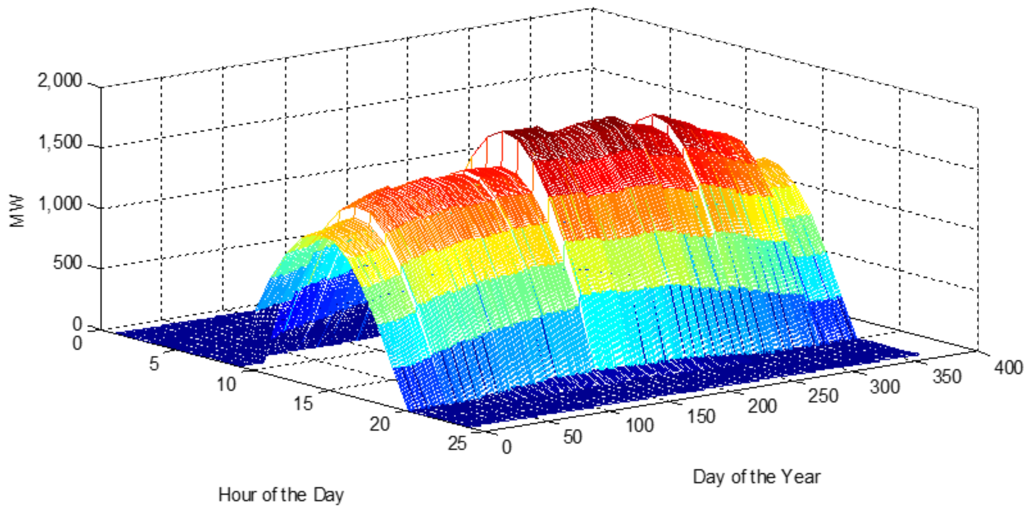


Figure 3.17: A Mesh of the Daily Solar Plant Electricity Generation computed for the Whole Year with a Fixed Tilt Angle of 16.38° and azimuth angle of 7.53°

Figure 3.18 shows the plot of the maximum energy generated over a year computed using optimum value of β for each month and for β set to the average daily optimum of five summer months with and without the consideration of monthly dust accumulation. The case where 'optimization assumes no dust exists' is the commonly computed value in the literature; these literatures completely ignore the presence of dust in environments such as in KSA. That means that, it is not possible to achieve the computed theoretical values in practice; the best that such computation can achieve in that case will be 'the optimization assumes dust exists but not considered' scenario. Thus, the approach proposed in this section, the 'optimization includes dust consideration' scenario, contributes additional 400 MW to the energy generation compared to the case where 'the optimization assumes dust exists but not considered'.

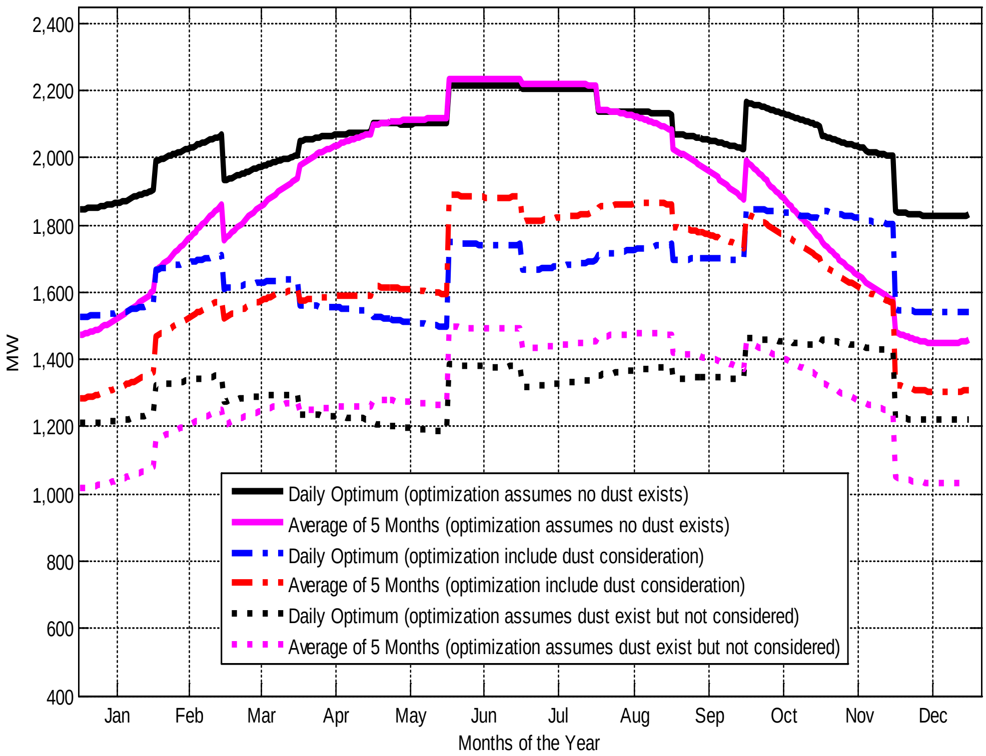


Figure 3.18: Maximum PV Plant Generation with Different β Values for the Whole Year with and without the Consideration of the Average Monthly Dust Accumulation

3.7 Discussion

So far, this chapter has presented an algorithm for finding optimum tilt and azimuth angles for PV systems matched to the timing of the peak demand on the load profile. The optimum values of tilt and azimuth angles for a PV system is obtained by the optimization (maximization) of the amount of total energy that can be generated by the PV system for a given period of time (such as a day, a calendar month, and a season). In this chapter, a possible way of managing electricity peak demand is proposed. In order to improve national electricity generation capacity in a practical way, the deployment of PV panels with slope and orientation that are optimized with respect to the timing of the demand profile can be effected. The algorithm to achieve that, as presented in this chapter, addresses this problem by obtaining the value of the tilt angle and azimuth angle that will enable the extraction of the maximum amount of the solar radiation that is harvestable given an assumption about the cleaning regime for the panels.

3.7.1 Without Dust Effect Consideration

The optimum values of PV systems' tilt and azimuth angles for the city of Riyadh (KSA) were determined using the presented algorithm and the main conclusions that may be drawn from the results are as follows:

1. The optimum tilt angle varies for each day of the year; for Riyadh it varies from the minimum value of $-7.33°$ on the 172th day of the year to a maximum value of $50.01°$ on the 355th day of the year.
2. The optimum tilt angle varies for each month of the year; for Riyadh, it varies from the minimum value of $-6.92°$ in June to a maximum value of $49.57°$ in December.
3. The optimum daily tilt angle that generated the maximum energy is found to be $-5.79°$ which occurs on the 152nd day of the year.

The following choices are available for the adjustment of the tilt angle in order to harvest solar radiation:

a. Movable tilt and azimuth angles: setting the tilt and azimuth angles to the different values daily or monthly which can gives high efficiency output but it will impractical from economic prospective.
b. Yearly best average (fixed): Setting the tilt angle to the value of 'best' of the year (that is, a fixed value throughout the year).
c. Summer best average (fixed): setting the tilt angle to the value of the 'average of 5 summer months' (May to September), that is, a fixed value throughout the year).
d. Summer and winter best average (fixed): setting the tilt angle to the value of the 'average of 5 summer months' in the summer months (May to September) and setting it to the value of 'average of 7 winter months' for the rest of the year (that is, change the tilt angle to one value in the summer and to another value for the rest of the year). This choice harvests more energy than the two previous choices, however, changing the tilt angle for $7,972,500$ of PV panels twice a year can be difficult from practical and economic considerations.

Thus, in order to address the peak load problem, a solar PV generating plant with fixed orientation is the most reasonable for practical reasons, fixing the tilt angle to the value of average of daily optimum tilt angle of five months throughout the year (that is, 2.36°) will therefore be a good choice.

3.7.2 Considering the Effects of Dust Accumulation

a. The maximum power generation in a year is up to 1,850 MW (as against 2,214 MW when dust was not considered) and the monthly optimum tilt and azimuth angles at which that occurred are 34.11° and 6.24°, respectively, which is on the 274th day of the year (that is, 1st day of October).
b. For the whole year, tilt and azimuth angles can be fixed to 16.38° and 7.53°, respectively, which are obtained by taking the average values of the angles for five summer months (May to September); with this, the solar plant generated its maximum energy of 1,891 MW on the 152nd day of the year.
c. Consequently, the energy production from PV that can be supplied during the peak demand when the tilt and azimuth angles are based on the 'average of 5 months' ranges from a minimum of 1,284 MW (in January) to a maximum of 1,891 MW (in June).

3.8 Summary

Using the proposed algorithm, numerical results for the case of Riyadh city in KSA were shown. The problem of finding the optimal tilt angle β and azimuth angle z that gives the maximum solar energy from a set of PV generation plants with total capacity of 2.4 GWp in the city of Riyadh and inverter efficiency of 98%, given that it is known that the peak demand for electric power in KSA occurs between 12:00 and 17:00 in summer months, was considered. For the total installed generation capacity of Riyadh city as of 2015, setting the tilt angle to the value of the 'average of 5 months' (that is, a fixed value throughout the year) is a reasonable choice from a practical point of view. As a result, the production of electricity that can be supplied during peak demand from PV systems where the tilt and azimuth angles are based on the 'average of 5 months' ranges from a minimum of 1,448 MW (in January) to a maximum of 2,233 MW (in June).

The issue of the desert-like climate of KSA that encouraged dust accumulation on PV solar panels was addressed by modifying the algorithm (in particular, the objective function) and the optimal slope and orientation of PV solar panels were found that take into account this effect. The results show that the maximum energy generation in a year is up to 1,885 MW (as against 2,332 MW when dust was not considered) and the tilt and azimuth angles at which that occurred are 34.11° and 6.24°, respectively, which is on the 274th day of the year (that is, 1st day of October). For the whole year, tilt and azimuth angles can be fixed to 16.38° and 7.53°, respectively, which are obtained by taking the average values of the angles for five summer months (May to September). With this, the solar plant generated its maximum energy of 1,852 MW on the 152nd day of the year.

Chapter 4: Reducing High Energy Demand Associated with Air-Conditioning Needs in KSA

4.1 Introduction

In KSA, 52% of the energy generated in the country is consumed by residential buildings and, during the summer, 60% of the energy consumed by these buildings is due to the air-conditioning systems (Alrashed & Asif, 2014). The need for air-conditioning systems in the buildings is due to the low quantity of rainfall and the high temperature during the daytime in the country which is similar to other countries with desert-like climates. The average summer temperature in KSA can reach up to 45 ^{o}C – typically, the temperature rises soon after daybreak and remains high until sunset.

One of the major causes of the high energy consumption due to air-conditioning is the fact that majority of KSA buildings, about 70% (SEEC, 2017b), are not thermally insulated (other important reasons also include the highly subsidized cost of energy bill, minimal use of energy efficient products and the weakness of energy products' control standards (Mujeebu & Alshamrani, 2016)). Consequently, a major part of air-conditioning loads is the heat transmission through the walls of buildings and roofs (Al-Sanea & Zedan, 2008). Another major contributor to the high electricity consumption is occupant behaviour; for instance, many of the customers in KSA leave their air-conditioning units to run non-stop throughout the summer months (Taleb & Sharples, 2011; Mujeebu & Alshamrani, 2016). Over 73% of households in KSA turn on their air conditioning systems from between 10 and 24 hours on a typical day during the summer months (Aldossary, Rezgui & Kwan, 2015). Thus, because in most cases these long AC running times are not essential for comfort, customer behaviour is one of the most important causes of inefficient energy use for AC.

This chapter will investigate some solutions to the problem of high-energy demand associated with air-conditioning needs in KSA in residential building. It is clear that improvements that will effectively encourage reduced operation of air-conditioning units will achieve savings in the total energy consumption of these buildings. These savings are particularly important during the peak duration of electricity demand. Typical residential buildings of KSA will therefore be modelled and simulated using the DesignBuilder software in order to understand the different proposed solutions in the form of modes of operations of ACs that can effectively reduce the energy consumption of air conditioning units. The potential impacts in terms of the achievable electricity savings of the different modes of AC operation for the residential houses in Riyadh city will be presented. In addition to using data of the typical house types and their actual dimensions and building materials, the simulation will also take into account typical behaviour of occupants of residential buildings in Riyadh city making use of behavioural data obtained through a survey that was carried out.

4.2 Literature Review

4.2.1 Occupancy Behaviour

The behaviour of building occupants is one of the four most important factors influencing the building's dynamic thermal properties – in particular, the building's heat gains and the occupants' comfort requirements. The other three important factors are the building's physical properties (e.g. location and orientation), the thermal control equipment installed in the building (e.g. heating, ventilation, air-conditioning system and hot-water heating system), and the buildings outdoor environment (e.g. temperature, and solar radiation) (Mahdavi & Pröglhöf, 2009). Of these factors, occupancy behaviour is, by far, the most difficult to model largely because humans, by their very nature, are unpredictable animals (Robinson, 2006). The mere presence of humans on its own within a building establishes other activities, such as the emission of carbon dioxide and water vapour or the use of electrical appliances for lighting, heating or cooling, etc., which affect the indoor behaviour of the building (Kwok & Lee, 2011). Moreover, humans adjust the appliances and/or the surrounding of their environment in order to optimize their comfort (such as turning ON the ACs or opening the windows to affect their thermal comfort, or adjusting the lighting to affect their visual comfort). Thus, it is particularly difficult to predict the occupancy behaviour of an individual building but trends of behaviour can be studied for a group of buildings in order to extract long-term observation data (Mahdavi & Pröglhöf, 2009).

Occupancy information allows occupancy prediction which is very important for scheduling in buildings' climate control (Oldewurtel, Sturzenegger & Morari, 2013). The ability to predict both short-term vacancies (e.g. intermittently entering and leaving a room or home, moving from one room in a house to another, or leaving the house for work, etc.) and long-term vacancies (such as business trips, illnesses and holidays) can provide meaningful energy savings (Bloomfield & Fisk, 1977).

A major contribution to high electricity consumption in KSA is occupant behaviour. A large number of customers in the country leave their ACs turned ON throughout the summer months (Taleb & Sharples, 2011; Mujeebu & Alshamrani, 2016). The low price of electricity due to high subsidies leads to the lack of awareness of the high cost of energy generation especially during peak hours and provides no incentive for the conservation of electricity. Occupancy behaviour encompasses the adjustment of thermostat settings and the opening and/or closing of doors and windows by the occupants. It also includes whether the air conditioning systems are turned on or off during the presence or absence of occupants during the day or in the evening. Because it is important to maintain the comfort of a building at satisfactory levels in response to the dynamic environmental factors of buildings such as occupancy behaviour, a possible method of maintaining such comfort is to measure occupancy level of buildings, which can be achieved using sensors, and use that information to control the air conditioning system.

Representative models describing occupancy behaviour of KSA's residential buildings are not available as far as the author is aware. These models are needed for computer simulation of the energy consumption of KSA's residential buildings in order to propose solutions that will make energy savings achievable. In this respect, a survey is carried out and described later in this chapter to understand occupancy behaviour times in which rooms are occupied and usage of electricity consumption appliances. This is the first attempt to describe occupancy behaviour of residents of KSA to the author's knowledge.

The insight gained from the survey will be used for the computer simulation of residential buildings' energy performance to understand the energy savings possible if ACs are used in a more energy efficient manner.

4.2.2 Occupancy Sensor Technology

A reliable and quick means of determining when the home is occupied, or when occupants are asleep, and the method of determining when to switch off the air conditioning system are major challenges facing the control of air conditioning systems in residential buildings. In relation to determining when to switch off, switching on and off arbitrarily or pre-cooling the house too early or switching off too late can cause energy wastage.

Motion sensors, passive infrared sensors, and ultra-sound occupancy sensors are among those that have been suggested for occupancy detection. Motion sensors are, very often, poor occupancy sensors and their careless use could encourage uncomfortably large temperature swings. Passive infrared and the ultra-sound occupancy sensors are well known to have limited range of occupancy detection and to give inaccurate results when occupants remain motionless for a long time (Aftab *et al.*, 2017). The occupancy of a target place can be monitored over a given period of time and the data collected can be used as historical data for the prediction of future occupancy of the target place using various techniques such as, for instance, neural network (Mozer, Vidmar & Dodier, 1997) and the hidden Markov model (Lu *et al.*, 2010). Since the estimates of future occupancy using historical data are probabilistic, the accuracy of the predictions is sensitive to changes in occupants' life pattern and is challenging to implement successfully for shared places (such as workplaces, lecture halls, etc.) where the number of exceptional cases is common.

Recently, real-time video based occupancy recognition systems are being proposed (Pedersen, Nielsen & Petersen, 2017; Aftab *et al.*, 2017) and it has been claimed that these technologies can provide up to 99.7% of accuracy (Goldsworthy, 2017; Petersen *et al.*, 2016) but the commercial viability of using such expensive appliances and their implication for the privacy of the occupants, are important problems that are yet to be resolved. Other data-based sensor technologies that are less expensive and available for occupancy detections are the Wi-Fi (where occupancy is based on the presence of the mobile phone devices to the household's Wi-Fi network) (Zhao *et al.*, 2015) and the GPS location sensor (Gupta, Intille & Larson, 2009). However, there are concerns over the intrusive nature of the sensory data of these methods (Pedersen, Nielsen & Petersen, 2017).

Another attractive and relatively cheap device that has been used as an occupancy detector is the carbon dioxide (CO_2) level detector since the level of CO_2 is an indicator of human presence to a large extent (Federspiel, 1997; Zhao *et al.*, 2015). The accuracy of using this method for occupancy detection in a residential flat of two persons is reported to be around 46% which is low (Cali *et al.*, 2015). Another disadvantage of this occupancy detection approach is that it requires very detailed physical description of the room and its condition (such as room volume, window/door sizes, occupants' CO_2 production, and so on) and these parameters can vary over time (Pedersen, Nielsen & Petersen, 2017).

Furthermore, systems that automatically sense occupancy status and occupants' sleeping pattern of homes and use these parameters to change the thermostat settings of air conditioning systems in order to save energy already exist. For instance, a case study of a solar-assisted air-conditioning system that uses real-time occupancy sensor thereby reducing energy consumption is presented in (Rosiek & Batlles, 2013). The main idea is that this system identifies optimum operation sequence – using real-time occupancy monitoring – and operates on the actual load conditions (not on maximum load that it is designed for) which leads to energy savings. Several research works have been published that address the methods for automatically controlling the settings of thermostats. A technique based on occupants' mobility prediction (using contextual information obtained by mobile phones, historical pattern and route classification) that provides a solution for efficient thermostat control is presented in (Lee *et al.*, 2013). This technique is reported to be capable of predicting users' arrival or departure transit with up to 70% accuracy and with error margin of about 10 minutes, thus, reducing energy consumption by about 26%. However, the accuracy of the prediction algorithm severely suffers with increase in the number of traffic congestion in the areas around the building. Moreover, the algorithm does not work with some of the most popular mobile phone platforms (including Android and iOS) because it requires the information of the neighbouring cell identity which most recent mobile platforms do not provide access to.

In conclusion, despite issues with individual sensor techniques, reliable occupancy detection and prediction at affordable cost will be possible in the near future as technology improves, probably by combining multiple sensor data sources. The practicality of this approach has already being demonstrated in other areas (see, for example, (Boait & Rylatt, 2010) for automatic operation of domestic heating).

4.2.3 Reducing Peak using Demand Side Management and Demand Response

The terms Demand Side Management (DSM) and Demand Response (DR) are often used interchangeably. For our purpose, on the one hand, DSM is the adjustment of consumer energy demand through customer behavioural change as a result of education or financial incentive. The goal of DSM is primarily to encourage customers to use less energy during peak hours, which is often achieved by moving the time in which energy is used to off-peak times such as early morning, evening, or weekends. In other words, DSM is a tool for shifting load from peak to off-peak periods in order to increase the utilization of generating plants (Strbac, 2008). Thus, to reduce their electricity bills, customers can schedule most of their loads for off-peak hours or store power during off-peak for later use during peak times (Adika & Wang, 2014). A consumer’s total energy consumption is not necessarily reduced by DSM. What DSM does is that it is capable of reducing the need for investment in new power plant and network infrastructure projects required for meeting peak energy demands (Strbac, 2008; Gottwalt *et al.*, 2011; Lee, Kim & Kim, 2011).

On the other hand, DR is the technology that enables economic rationing system through the automatic adjustment of consumer energy consumption by the electric utilities for the better matching of consumer demand with the energy supply. To achieve this, utilities take control of demand of the customers and offer low price of electricity for them during off-peak hours and high price of electricity during peak periods. Sometimes, involuntary rationing through rolling blackout during peak periods is also used by the utilities to implement DR. Thus, utilities, driven often by economic considerations, are able to take actions to respond to supply shortage during peak periods through DR. These actions are based on the mutual agreement between the utilities and their customers (Siano, 2014; Yoon, Bladick & Novoselac, 2014; Mohagheghi *et al.*, 2010).

In DSM, efforts in the demand side are invested in motivating customers' behaviour in order to improve energy efficiency and the match between available supply and demand. For example, DSM can come in the form of allowing customers to manage different loads (by shifting the loads from peak to off-peak periods) such as air-conditioners, refrigerators, heating, and so on, in their homes. Economic constraints, efficiency, reliability, and renewable energy integration are some of the most important issues affecting the stability of power system infrastructure.

DR has become an essential part for managing the imbalance in electric grids (Yan *et al.*, 2015; Yuan & Hu, 2011; Xue *et al.*, 2014). In relation to air conditioning systems, DR can also be achieved by the utility company remotely changing the thermostat settings of air conditioning systems. Through DR, utility companies and customers save cost and energy. Some of the challenges of the DR approach when extended to residential sector include finding the optimum schedule and the ICT infrastructure that can be deployed to actualize DR (Haider, See & Elmenreich, 2016; Adika & Wang, 2014; Darby & McKenna, 2012) and managing the conflicting objectives of minimizing energy cost (for the customer) and the available energy with minimum cost (for the utility company) is the key requirement (Haider, See & Elmenreich, 2016). An algorithm for controlling the energy demand is presented in (Chen, Chen & Maxemchuk, 2012) where a fair share of power is allocated to residential air conditioners on a smart grid; in this approach, customers request from the utility company a thermostat setting for their air conditioners; the utility company on its part will allocate the available power to each residence using algorithms with fairness metrics and the awareness of capacity constraints on the network.

Later in this chapter, three modes of air-conditioning systems' operation will be presented. The first two modes that will be discussed fall into the DSM category of electricity management strategy while the third mode of operation falls into the DR category.

For modes running on the DSM paradigm, air-conditioning systems run on a non-continuous and scheduled basis; smart thermostats that are able to learn customers' occupancy behaviour are installed such that energy consumption is reduced during non-occupancy periods, over the periods of the day or week. Moreover, such thermostats are also equipped with features for pre-cooling periods which start the air-conditioning systems prior to room occupation depending on the thermal mass of the building and the capacity of the air conditioning unit relative to the heat load.

The fact that a significant amount of energy saving can be achieved – even by a small increase of AC thermostat settings e.g. 1^{o}C or 2^{o}C – has been largely ignored in practice but the concept in not new within the research community (see, for instance, (Vine, 1986; Maheshwari *et al.*, 2001)). Researchers have also reported that setting the thermostats to one value throughout the summer and to another value throughout the winter (with the two values determined by averaging the daily optimal values) can significantly reduce air-conditioning loads while still achieving the desirable thermal-comfort for occupants (Al-Sanea & Zedan, 2008). Due to the difficulty of making enough residents manually turn off air conditioning systems (usually as a result of weak financial incentive for the residents), the saving that can be realised is hard to achieve (Sachs, 2004) even though the cumulative savings for a nation could reach tens of billions of dollars annually (Lu *et al.*, 2010). This motivates the need for a situation where the utilities can automatically control the thermostat settings of the air conditioning systems of households if and when appropriate without requiring daily thoughts or actions from occupants. Thus, to save energy, in the DR mode, the utilities can remotely set the thermostats to 24^{o}C during peak hours – with the agreement of customers based on DR paradigm. In KSA, households are increasingly being equipped with smart metering; in fact, SEC rolled out 55,000 smart meters in 2015 with the aim of improving meter reading accuracy, providing better energy conservation and management, and identifying energy consumption patterns in real time (SEC, 2015). The installation of such smart meters will allow consumers to monitor the load and manage their air conditioning systems' electricity consumption (Gottwalt *et al.*, 2011).

4.3 Methodology

Figure 4.1 provides a high-level view of the methodology that has been adopted in order to investigate solutions to the problem of high-energy demand associated with air-conditioning needs in KSA in residential buildings. A simulation-based methodology is adopted as it allows the simulation of different AC control schemes that are proposed. Moreover, this approach also allows the study to focus on many schemes at the same time without the cost of purchasing the hardware (equipment and sensors) and the time for setting up different testing conditions that would have been necessary if an experimental approach is considered. In addition, the proposed control techniques are not available in the market. Having set out the goal and presented a literature review in the preceding sections of this chapter, the sections that follow will provide details on the research carried out in relation to the survey on energy use and customer behaviour conducted as part of this research and the commonly used construction materials and house types in KSA. These elements will inform the choice of the modelling parameters that will be used for the computer simulation of residential building energy consumption behaviour in section 4.5.2. The procedure for carrying out the computer simulation for different modes of operation of AC are also described in detail in section 4.5.3. Thereafter, the analysis and discussion on the simulation results are provided to give an insight into energy consumption savings achievable for the various modes of AC operation.

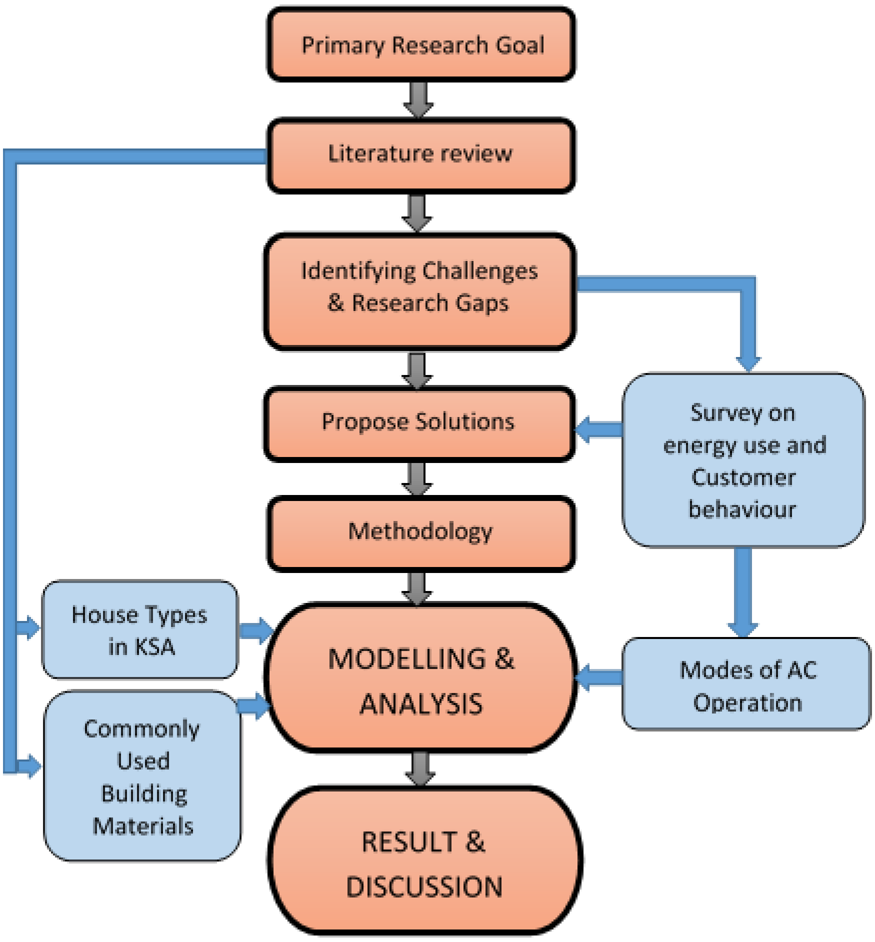


Figure 4.1: Block diagram showing a high-level view of the methodology adopted

4.4 Energy Use and Customer Behaviour Survey

Developing a representative model of occupancy behaviour for computer simulation and/or for practical planning and design of building in relation to air conditioning systems is important and can be a very challenging task due to the lack of reliable data that covers a representative range of human behaviour for constructing such a model (Goldsworthy, 2017; Li & Jiang, 2006). The three methods that have commonly been used for obtaining such data are as follows (Goldsworthy, 2017): (i) survey data that characterizes the switching 'ON and OFF' behaviour of occupants, (ii) measurements taken from several households by monitoring household-level sub-circuits to determine probabilities for switching ON and OFF the air conditioning systems, and (iii) averages of energy consumption data in addition to associated weather and demographic statistics, among other determining factors.

It is common to use survey-based information that is validated and/or supported by actual measurements and computer simulation in studies of this nature (Goldsworthy, 2017). In this thesis, a survey has been undertaken to investigate some of the behavioural factors causing high-energy consumption in Saudi Arabia's domestic buildings. The survey questionnaire was designed, piloted and distributed to people of different gender and regions across Saudi Arabia in order to obtain information related to building design, occupants' behaviour with regard to electricity use, perception on renewable energy, and so on.

Besides the online survey, interviews were carried out with several residences from two regions in KSA. This was done to investigate these residencies behaviours regarding energy consumption, particularly their AC use. Actual readings of household-level electricity consumption from the different types of KSA housing units were measured using applications available on customer mobiles. This could also provide an overview over the previous three years of consumption.

The questionnaire was divided into the following four main sections:

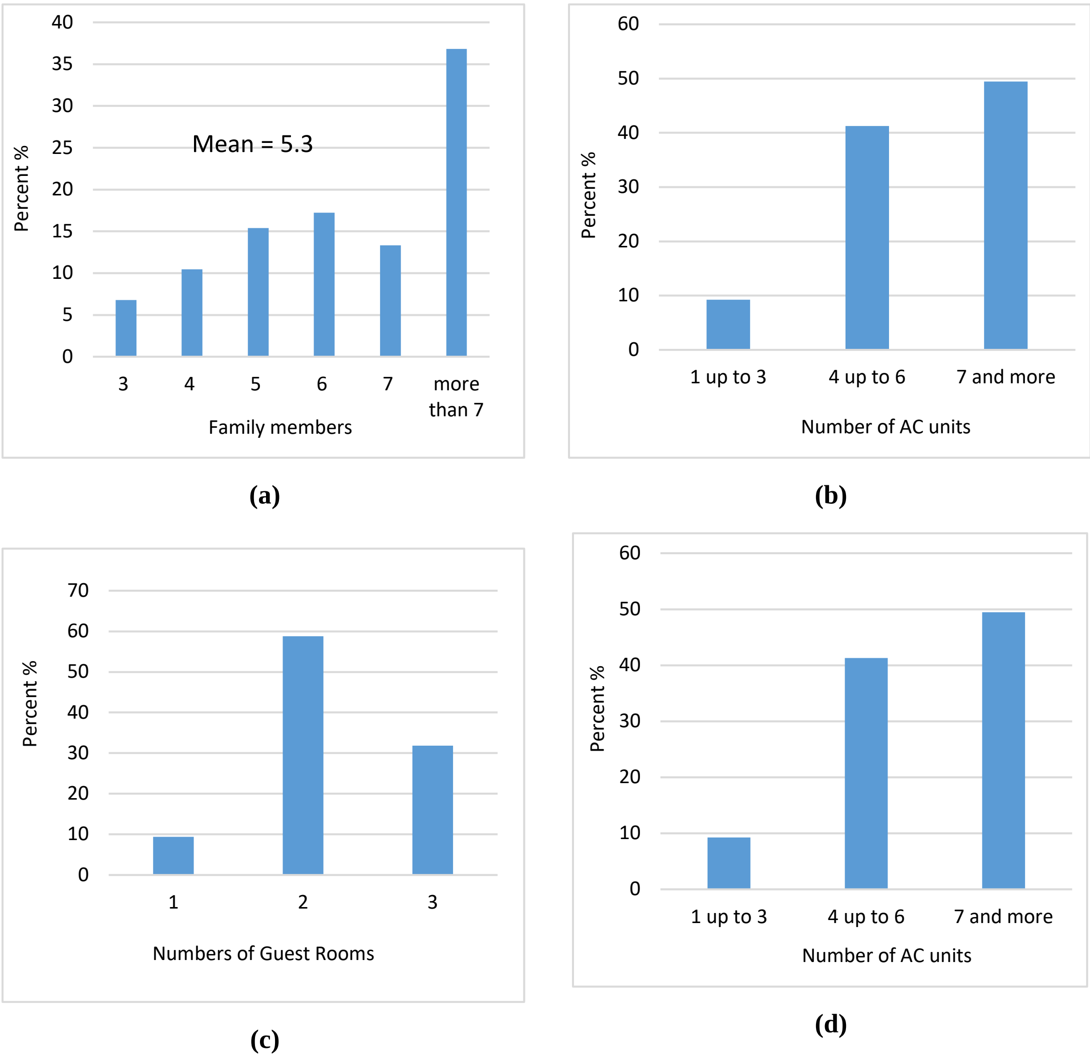
(1) A section investigating accommodation data such as the number of guest rooms, bedrooms and bathrooms, as well as accommodation types

(2) A section investigating the high electricity consumption of home appliances by type and numbers

(3) A section investigating the occupants' behaviour regarding times rooms were occupied and usage of high electricity consumption appliances.

(4) A section exploring people's perceptions of renewable energy in homes.

Both English and Arabic languages were used in the questionnaire. The questionnaire of the survey were distributed to participants from the whole kingdom via email, WhatsApp, and Twitter. The online survey dissemination system was utilized because it was easier, faster, and less expensive than a printed survey (R Weible, 1988; Huang, 2006). The questionnaire was initially sent through relatives, friends, colleagues, and other acquaintances who further recruited additional acquaintances from their wide networks, such as friends and colleagues (Goodman, 1961). Consequently, the sample includes various respondents who came from all the regions of KSA. It is reasonable to assume that the survey has found the more common patterns of room occupancy and AC use, which are taken forward into the simulation studies. The detailed questionnaire is given in the Appendix A. In general, the questionnaire reached 451 participants; 383 of these completed and returned the forms. The demography of the respondents (i.e., family size, number of bedrooms, guestrooms, and AC units in the household) is given in Figure 4.2.



(a) **(b)** **(c)** **(d)**

Figure 4.2: Demography of survey respondents: (a) Family members; (b) Number of bedrooms; (c) Number of guest rooms; (d) Number of AC units.

The Saudi Arabian culture features extended families living together in large houses, referred to as villas; affluent families often own villas. The less affluent families often reside in individual houses that are referred to as traditional houses. The rapid growth in KSA's population required quick construction of cheap accommodation in the form of several flats (apartments) within individual buildings (or apartment blocks). Detached single- or two-storey houses were also built with rapid construction. In some cases, the two-storeys were used as two separate floors (one floor on the top and the other at the bottom). Regardless of whether a residential building is a villa, a traditional house, a flat, or a single- or two-storey house, the rooms were large; the average property in KSA is more spacious than its equivalent in Western Europe. Therefore, from the survey, of the total number of respondents, 40% live in villas, 41% live in flats, and fewer than 20% live in traditional houses. Overall, 90% of the respondents have more than one guest room (unlike in the English culture where a guest room often denotes a room within the house where guests are presented to sleep, a guest room in the Saudi culture is more or less a reception room where guests are received and served; these rooms are typically larger than bedrooms and, as custom, guests do not normally go beyond these guest rooms. Furthermore, 58% of respondents have two guest rooms, and 33% have three guest rooms. Also, nearly 50 % of respondents have seven or more AC units at their homes.

The bar charts in Figure 4.3 provide information on the household behaviour in KSA. Some highlights from these results include:

- The guest rooms are occupied mostly one day in a week.
- The main bedrooms of most respondents are occupied between 7:00 pm and 7:00 am the following morning.
- 63% set their AC thermostats to between 18^{o}C and 20^{o}C while 21% set it to between 21^{o}C and 23^{o}C.
- 66% rarely or never shut down their ACs during the summer months compared to 22% that usually do. The remaining 12% fall between these two extremes.

Thus, it is clear that the behaviour of AC users in KSA offers potential for substantial energy savings.

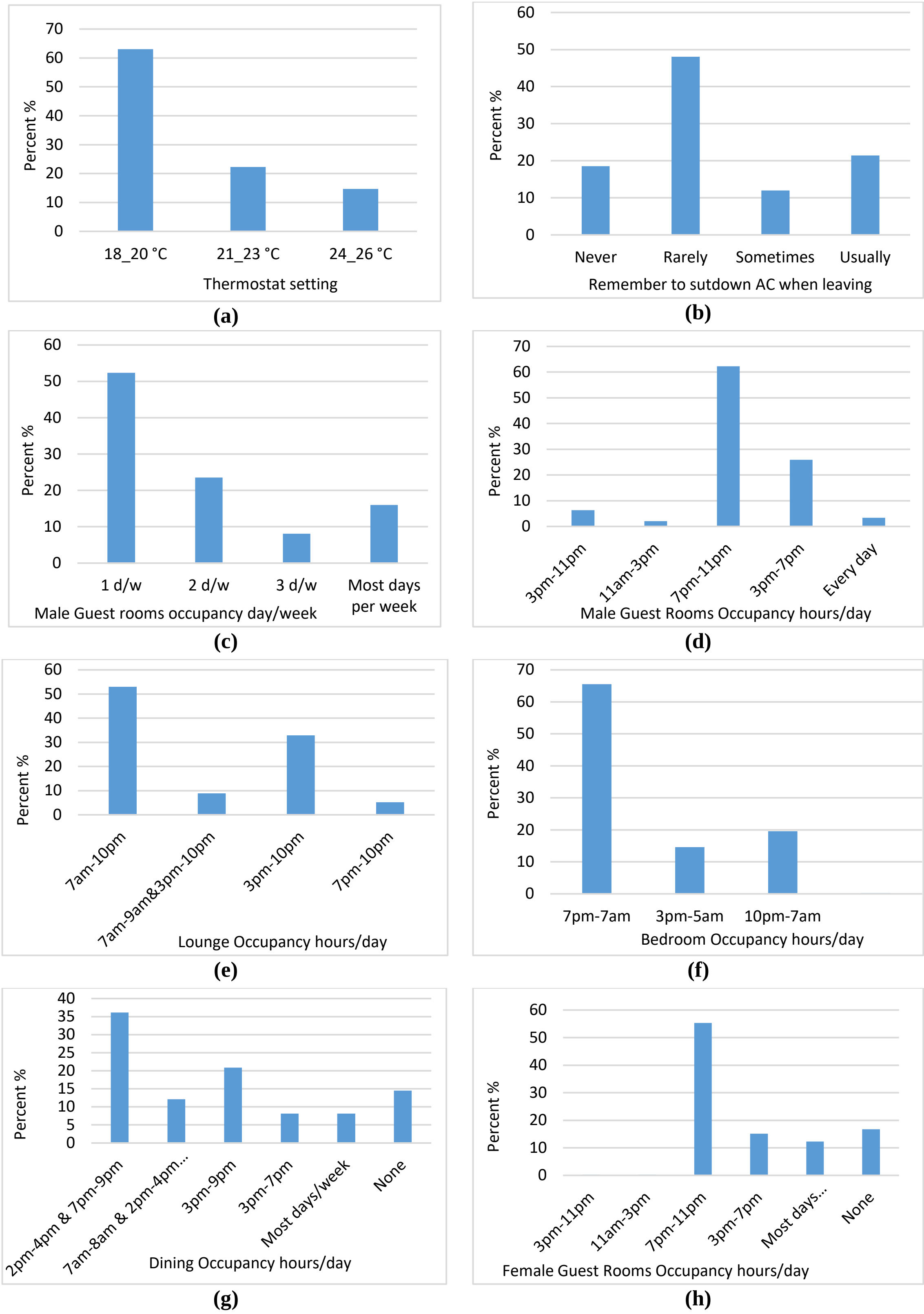


Figure 4.3: KSA's household occupancy behaviour: a) AC thermostat setting; (b) Remember to shutdown AC when leaving; (c) Male guest room occupancy day/week; (d) Male guest room occupancy hours/day; (e) Lounge occupancy hours/day; (f) Bedrooms occupancy hours/day; (g) Dining room occupancy hours/day; (h) Female guest room occupancy hours/day.

4.5 Computer Simulation of Energy Consumption in Residential Buildings

4.5.1 Background on Simulation Software

Computer simulations are important software tools for evaluating energy performance of buildings – old and new. They enable the effects of the whole process of design, operation, and lifecycle processes and maintenance to be evaluated from concept to design. In addition, software tools are available that allow models of human behaviour and visual and thermal comfort to be incorporated into the computer modelling and simulation process of buildings (Fasi & Budaiwi, 2015; Dabaieh *et al.*, 2015).

There are several advantages of using computer-based modelling and simulations (Macdonald, Clarke & Strachan, 1999; Coakley, Raftery & Molloy, 2012); computer-based modelling and simulation:

1. Are less expensive and less time consuming than experimental methods.
2. Make possible the simulation of conceptual design, such as those found in the building energy management or control system design specification.
3. Can be used to validate results from experimental analysis.
4. Can be used for scenarios where the evaluation of the interaction between different building performance measurements is costly or difficult.
5. Can be used for simulating the effects of retrofitting existing buildings to understand and analysis the consequence of improvements.
6. Can be used for calculating the energy required to maintain a building under external inputs (such as, occupancy, weather, humidity, etc.) given the specification of it energy performance criteria (e.g. humidity, space temperature, time and duration of use of spaces, appliances' turning on and off patterns, etc.).
7. Can be used for simulating the dynamic behaviour of a building over a given period, such as a whole year, which gives designers and analysts the ability to predict the behaviour of the building under previously unknown or unobserved conditions; the simulation to predict the performance of the building can also be done at any stage of the design, and this often means that the benefit of simulation

outweighs its cost in most practical cases – especially with the decreasing cost of computer hardware, the increase in computing powers and the increase in the availability of open source software libraries for performing these simulations.

Despite the benefits and the progress made in the development of simulation software that are capable of modelling complex building systems and their environments, computer-based simulation are not without their disadvantages: These include the following (Macdonald, Clarke & Strachan, 1999; Coakley, Raftery & Molloy, 2012)

1. Not all simulation data and parameters of the building may be known or fully anticipated (introducing uncertainties and/or risk factors in the model) at the initial stage of the simulation.
2. The number of input parameters for obtaining a model that will be suitable for simulation can be very large. A good calibration technique is, therefore, important to obtain useful results.

The DesignBuilder® software was developed by DesignBuilder Software Ltd, based at Stroud, Gloucestershire, United Kingdom. It is a popular and commercially-available software tool used for modelling and simulating energy efficient and comfortable building designs. It has been selected among others computer software tools, including DOE-2, EnergyPlus, TRNSYS, and ApacheSim for simulation in this study, because it has an easy-to-use interface. It runs on the EnergyPlus software engine and allows modelling using real historic data of weather condition from ASHRAE worldwide design weather data (which affects solar gain, heat conduction, convection, and so on) for most parts of the world. It permits complex building geometries to be taken into account in the simulation process. Furthermore, it has useful built-in features that facilitate energy performance comparisons, detailed modelling of Heating, Ventilation, and Air Conditioning (HVAC) systems, and natural ventilation, which enable optimization of renewable energy systems for buildings' energy performance improvements. It also provides a simulation of cooling/heating design calculations over any period of time, such as a day, a week, a season, or a year. In order to simulate the thermal performance of a house using the DesignBuilder® software, the model parameters must be defined. Model parameters describe the physical characteristics (including plan and geometry), installed equipment or appliances, building purpose and occupancy behaviour, the geographical location and climate, and the nature of the surrounding environment, among others (Tindale, 2004).

4.5.2 Simulation Input Data

The subsections that follow, the materials used for building construction in KSA are described. The description is necessary in order to be able to choose the appropriate material for the modelling in the DesignBuilder software. This is then followed by the methodology used for simulation, which further describes household-type specific simulation parameters. The input data for location and climate for the simulation software is given in Table 4.1.

Table 4.1: Data input for location and climate

General	Location	RIYADH OBS. (O.A.P.)
	Source	ASHRAE
	Climatic Region	1B
	Latitude	24.70
	Longitude	46.73
	Elevation (m)	620.0
	Hourly Weather Data	SAU_RIYADH_IWEC
Time	Time zone	(GMT+03:00)
	Start of winter	Oct.
	End of Winter	Mar.
	Start of summer	April
	End of summer	Sep.

4.5.2.1 Saudi Building Materials

Characteristics of residential building and construction materials in KSA are summarized as follows (Kaneesamamkandi, Almujahid & Ali Al-Sanea, 2015; Lasker, 2011):

- Cement-based hollow building blocks with thickness of 15 cm or 20 cm and surface dimension of 40 × 20 cm^2.
- The walls of residential buildings consist of three layers, the external cement plaster, the hollow brick (with different thickness sizes depending on whether they are inner or outer walls), and the interior cement plaster.

Table 4.2, Table 4.3 and Table 4.4 show the description and thickness of the materials commonly used for outer (external) walls, inner (internal) walls and roofs of residential buildings in KSA (Ahmad, 2002), respectively.

Table 4.5 shows the summary of other input data for the simulation software. Schematic of a typical envelope of a two-storey building of a residential house under construction in KSA is explored in Figure 4.4.

Table 4.2: The external wall construction

Layers	Material Description	Thickness mm
1	Cement & sand light plaster	20
2	Concrete cavity block	200
3	Cement & sand light plaster	30

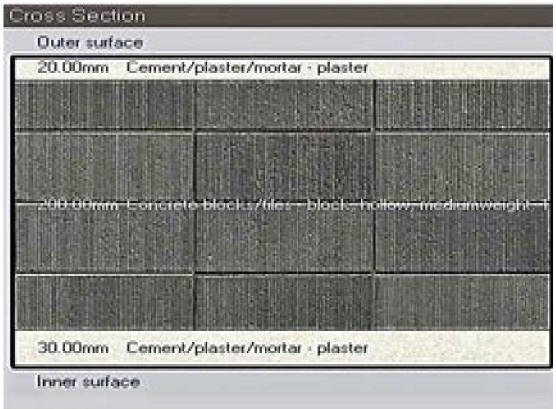


Table 4.3: The internal wall construction

Layers	Material Description	Thickness mm
1	Cement & sand light plaster	30
2	Concrete cavity block	150
3	Cement & sand light plaster	30

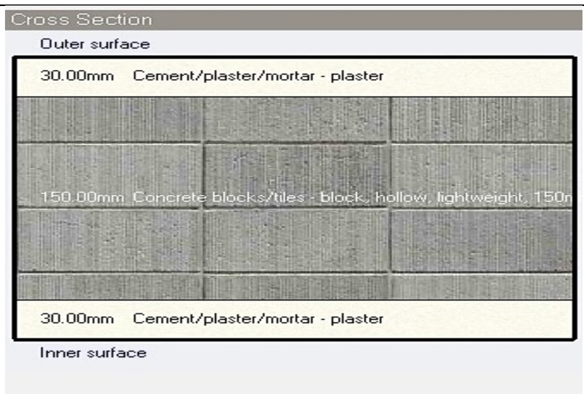


Table 4.4: The Roof construction

Layers	Material Description	Thickness mm
1	Roof tiles	15
2	Cement mortar/ sand	5
4	Concrete slab	200
6	Cement mortar	30

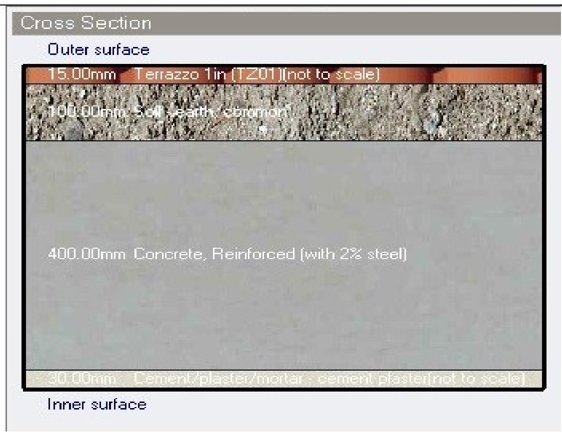


Table 4.5: Summary of the input data for simulation in DesignBuilder

Lighting	Openings	HVAC	DHW	Occupancy
Luminous and louvred ceiling Lighting is used with following properties: • Lighting energy= 0.4 W/m^2 • Radiant fraction= 0.37 • Visible fraction= 0.18	Single glazing windows (6mm) • Glass Area = 1m^2 • Solar set- point conduction ratio = 1 • Position= Inside	Split no fresh AC Air with COP= 2.2 • Based in electricity from grid	DHW COP = 2.5 Instantaneous hot water	density of 0.2 people/ m2 • Metabolic Activity= Light Manual Work • Metabolic factor= 0.9

Figure 4.4: Typical envelope of a villa buildings of a residential house under construction in KSA

4.5.2.2 Simulation Model Parameters

There are four types of residential housing units in KSA: a floor in two-storey house (which shall be denoted as House 1 in this thesis), a traditional house (which shall be denoted as House 2 in this thesis), a villa and a flat (or an apartment) (General Authority of Statistics, 2017). According to KSA's General Authority of Statistics (General Authority of Statistics, 2017), there are a total number of 829,670 housing units in Riyadh city, these are: 127,466 of House 1 type, 47,596 of House 2 type, 374,900 villas, and 279,708 flats and the average family size is 5.97. Further details on the four groups of residential buildings for Riyadh city that are used for this study are given in Table 4.6. This study will involve a single floor house, traditional house, a villa and a flat; these houses represents the majority of the residence in Riyadh city and the dimensions given in Table 4.6 are actual dimensions of representative real houses taken during the course of carrying out this study. The occupants of these houses also participated in the customer behaviour survey presented in the previous section. Also, the construction materials that will be presented later as well as the electricity bills are from these houses. This setup will enable the comparison and validation of the simulation results that will be presented in the subsequent sections of this chapter. The plans and geometric descriptions of House 1, House 2, the Villa and the Flat are given in Figure 4.5, and Figure 4.8, respectively.

Table 4.6: Details of the four groups of the single floor house, the villa and the flat

Building typology	Building's name	No. of floors	Building area m2	Number of occupants
A floor in two-storey building	House 1	1	177.69	4 adult+ 3 children
Traditional House	House 2	1	171.82	2 adult+ 4 children
Villa	Villa	3	279.72	2 adult+ 5 children
Apartment	Flat	1	102	2 adult+ 3 children

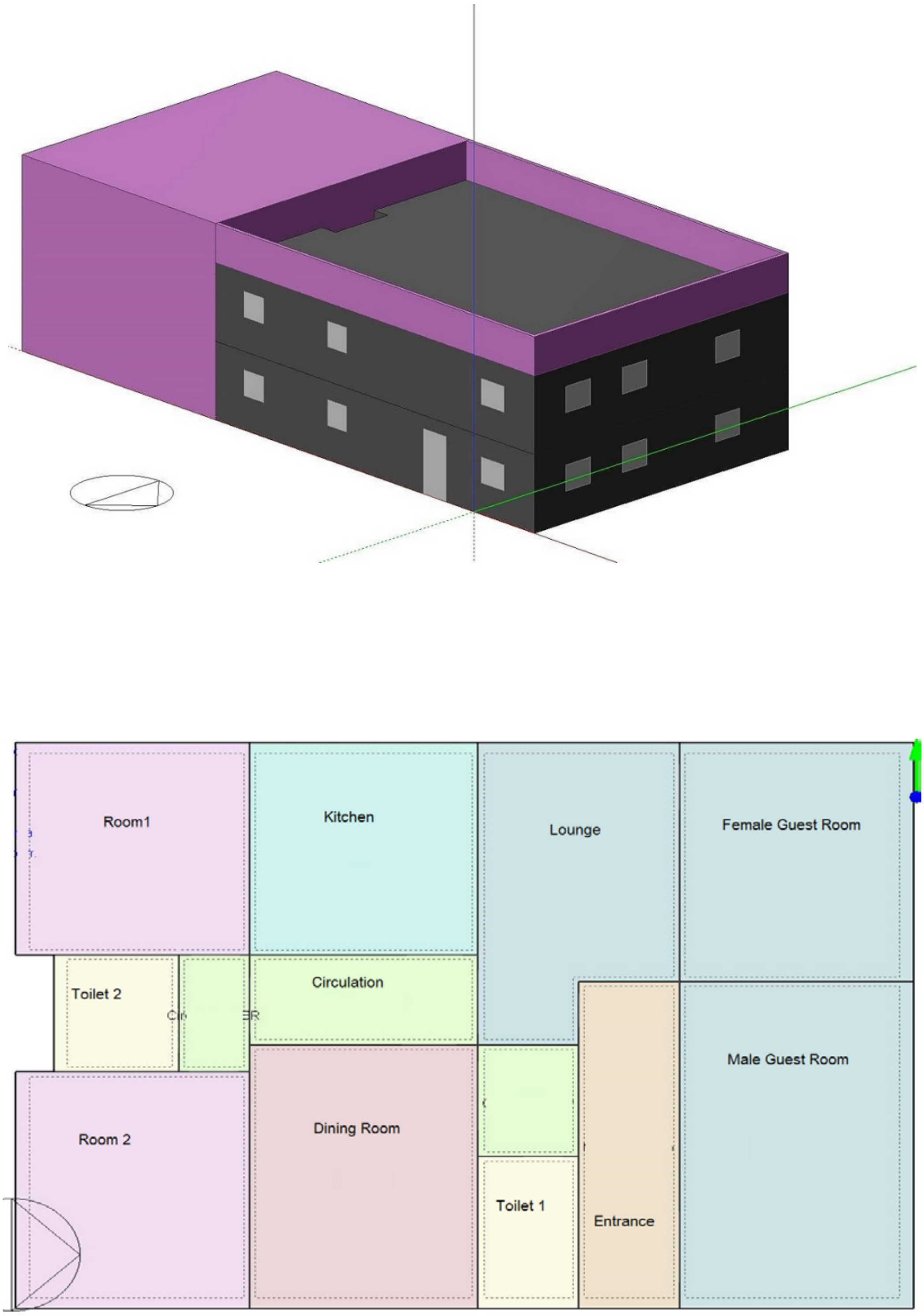


Figure 4.5: The plan and geometric description of the House 1 (ground floor)

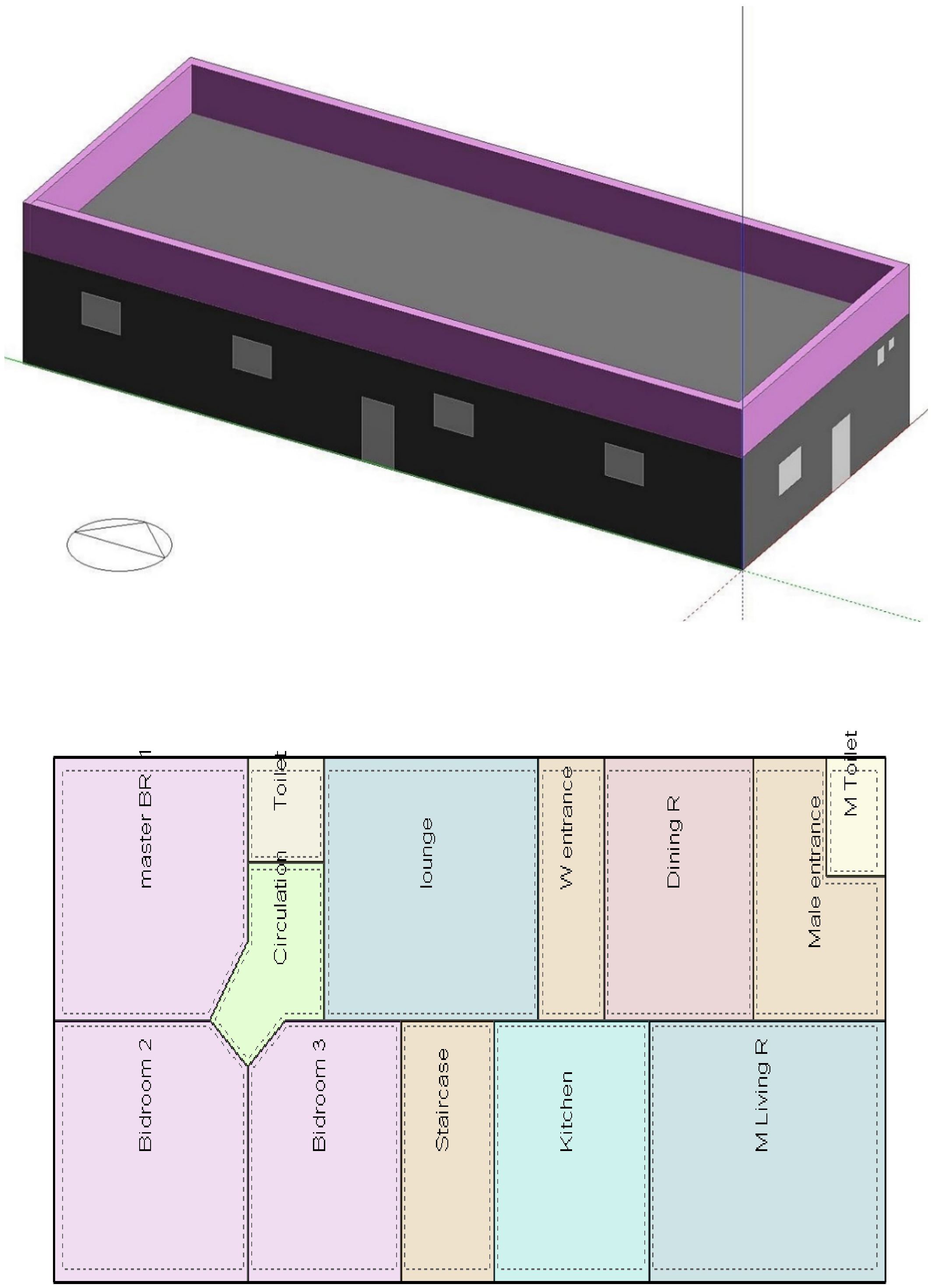


Figure 4.6: The plan and geometric description of the House 2

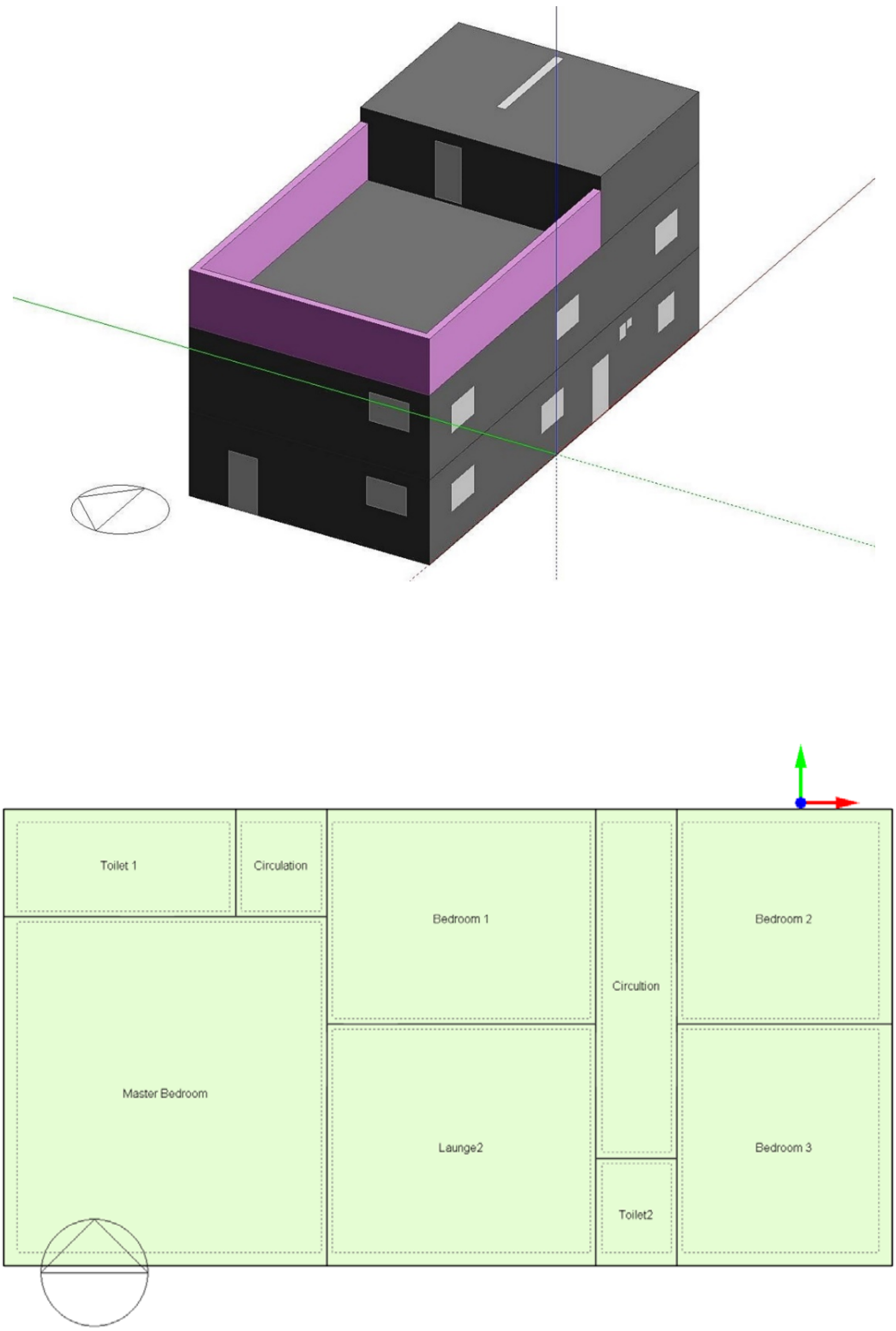


Figure 4.7: The plan and geometric description of the villa

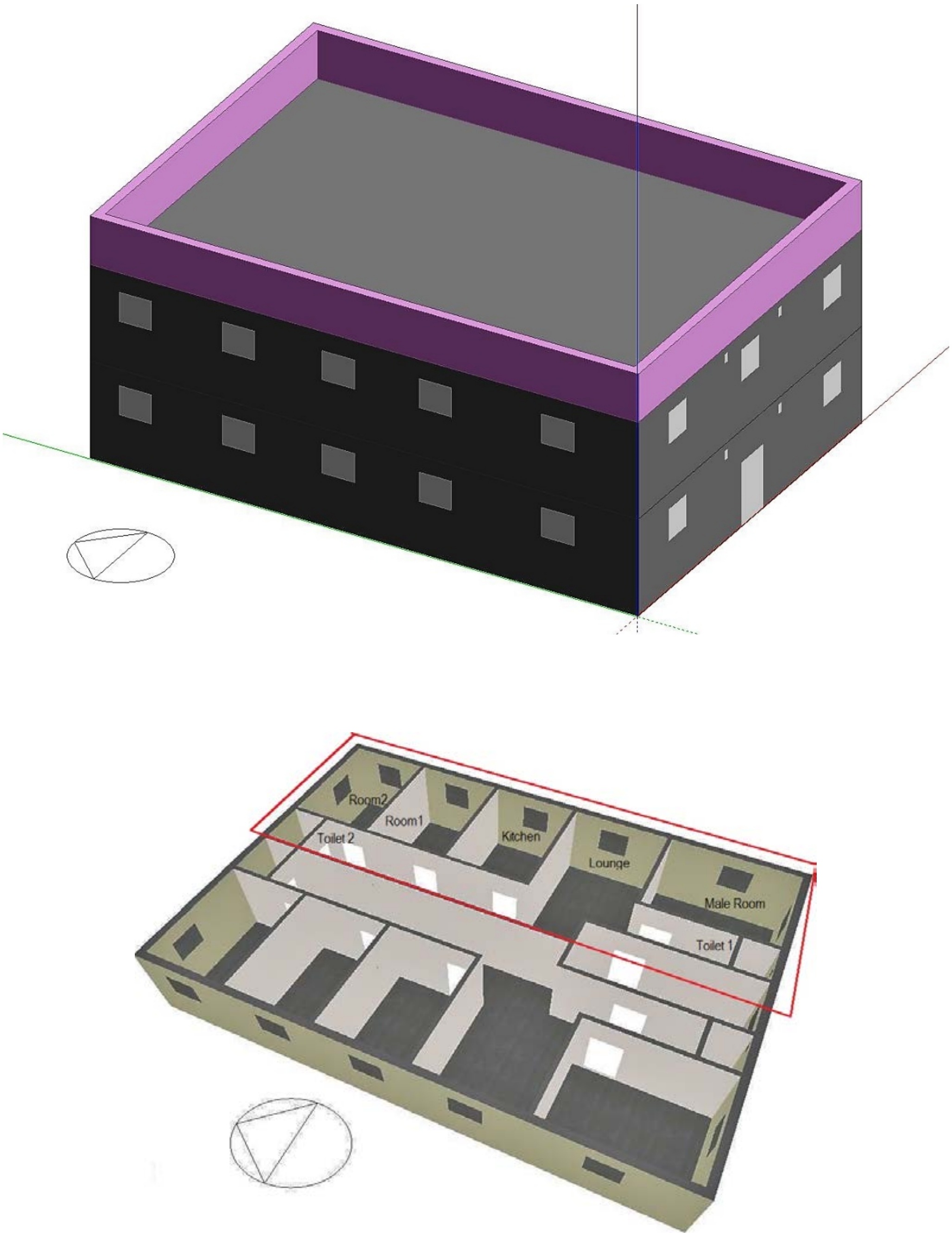


Figure 4.8: The plan and geometric description of the flat, red line defines the flat which is modelled in first floor

4.5.3 Methodology for Simulation Procedure

In order to simulate the thermal performance of a house, the model – which describes the physical characteristics (including plan and geometry), installed equipment or appliances, building purpose and occupancy behaviour, the geographical location and climate, and the nature of the surrounding environment, among others – has to be defined. For example, the model of a typical house in DesignBuilder is shown in Figure 4.9 where (a) shows the path of the sun for the house on the 4th July for any given year at time 2:00 pm in the afternoon and (b) represents the floor plan of the house.

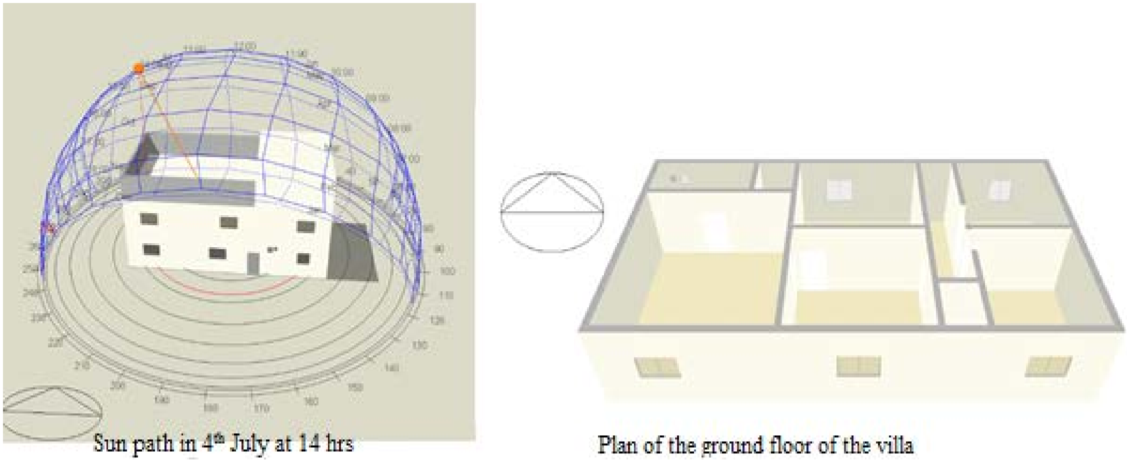


Figure 4.9: The model of a traditional house using the DesignBuilder software

The following steps describe the steps adopted for carrying out the simulation in this chapter:

- **Step 1: The selection of representative buildings from a group of buildings**

In this step, the set of buildings described above that represent the majority of residential buildings in KSA (Riyadh city, in particular) were chosen. In this study, the four representative houses have been chosen based on literature review and the survey that was carried out – one house was chosen from each of the four categories of houses in Riyadh: a single floor house, a traditional house, a villa and a flat.

- **Step 2: The definition of the buildings' geometrical parameters**

In this step, the geometry of the buildings is defined based on physical visits, interviews, and surveys that were carried out. The geometry is described in terms of the sizes of the room types (main rooms, guest rooms, kitchen, toilets, and so on) and the dimensions of the openings (such as the doors and the windows).

- **Step 3: Construction materials (thermal and physical characteristics)**

This step examined the construction materials and properties of house such as the materials for the external walls, internal walls, roofs, other parts of the buildings' envelopes, the shading, the glazing, etc.).

- **Step 4: The definition of energy consumption profile for the building models**

This step defined the result obtain from the survey, especially regarding energy consumption and occupants' behaviour including their activities and schedule of each room in relation to electricity appliances usage and, importantly, customer behaviour in relation the usage of air-conditioning systems. In addition, details regarding the numbers, types and operational strategies of AC are provided.

- **Step 5: Construct the models in DesignBuilder**

This involves creating models of the various houses using the DesignBuilder software tool. Modelling largely involves defining the model parameters (obtained from the previous steps) to the software tool. The model parameters defined includes the location (longitude and latitude), the orientation of the house, the climate condition (such as temperature and sun path), the house construction layout (such as details of the dimensions of external walls, roofs, internal partitions, floors, types of plasters, number of brick layers, etc.), the openings (such as glazing, shading, doors, and vents), the lighting (types and typical operation schedule), the HVAC system (their types, sizes, settings and operation schedule), and the activities (such as schedules for occupancy), among others. The ASHRAE standard 90.1-2013 is a cooling sizing technique for calculating the cooling design loads that is implemented in the EnergyPlus software (Ashrae.org, 2018). This system allows the conditions of the supply air that is delivered to the cooled zones in the building to be defined.

- **Step 6: Model simulation and thermostat setting (parameter) discovery**

The constructed models are used to simulate energy consumption of real KSA houses. The results are then analysed and used to adjust the model parameters in order to obtain reasonable correlation between the actual (observed) energy consumption of the residential buildings and the predicted (simulated) energy consumption. In other words, the modelling, simulation and analysis cycle is an iterative process. In particular, in order to ensure that the behaviour of the models that is built with DesignBuilder reflects the actual behaviour of the houses, the thermostat settings of the air-conditioning systems of the models have been adjusted, consistent with the behaviour survey. The monthly electricity consumption values obtained by simulation predict with reasonable accuracy those on the actual electricity bills of the actual houses. Figure 4.10 shows a sample of the actual monthly reading which is taken from a mobile application of the occupant of one of the houses and sent through WhatsApp to this author. The continuous operation which, a large number of people fall into according to the survey, will be used as a baseline for comparison among the following three modes of AC operations that are proposed.

- **Mode 1: The Scheduled Mode**

In this mode, the air conditioning is programmed based on the typical house occupancy behaviour pattern. In particular, to improve indoor comfort, the air conditioning systems are programmed to turn on automatically an hour before the occupants are predicted to arrive and to switch off automatically an hour after it is un-occupied, for instance. From the survey results, 66% rarely or never shut down their ACs during the summer months compared to 22% that always or usually do, and the remaining 12% fall between these two extremes. It means most people prefer to meet their homes air-cooled comfortably before their arrival into their homes and by turning their ACs ON before they arrive, there will be no need for them to leave the ACs turned ON throughout the summer. Likewise, by setting the ACs to switch off an hour after people must have left their homes ensures that if the room is occupied intermittently the AC is not subject to excessive short cycling (a situation where the AC system turn on and off irregularly without cooling the room properly). It is assumed that the houses are equipped with sensors that are able to detect occupancy and the occupancy weekly activities are logged on a periodic basis so that improvement can be made on the scheduling program in the next or future cycle of air conditioning systems' operations. The unique feature of this mode is that the room temperature set points of the AC thermostats are fixed to the value in which most people fix their thermostat settings according to the survey carried out in this research study (the fixed value is also backed up with the simulation carried out using Step 6.

- **Mode 2: The Advanced Control Mode**

This mode of air conditioning system operation has all the features of Mode 1 (the scheduled mode) except that there is the added feature of changing the room temperature set point of the air conditioning systems i.e. changing the setting of a thermostat from a lower temperature value when the room is occupied to higher value when a room in the house is not occupied for a short duration, say, less than 10 minutes. Then switch off the AC if the room stayed not occupied for a reasonable time say 1 hour. The additional feature in this mode is motivated by the need to save energy. In other words, by changing the thermostat setting from a lower value (which consumes more energy) to a higher value (which consumers lower energy) shortly after the room is unoccupied, energy is saved. The fact that a significant amount of energy savings can be achieved by even a small increase of thermostat settings e.g. 1°C or 2°C (Vine, 1986; Maheshwari *et al.*, 2001) has been largely ignored in practice but this fact is important for this mode. Also, in line with the electricity policies in KSA which recommends that householders set the thermostats of their ACs to 24 °C (instead of lower values) as there is no significant difference between this thermostat setting and those of lower values to home occupiers' comfort (SEEC, 2017a).

- **Mode 3: The Remote-Control Mode**

This mode of operation of air conditioning systems is significantly different from the previous two modes mentioned in that it is a Demand Response (DR) energy management approach that is being used. In this mode, the room temperature set points of the air conditioning systems are remotely controlled by the utility company during the peak time (for example, all the thermostats of the AC that are turned on in the subscribing customers' residences are remotely sets to a higher value of 24°C during peak times by the utility companies).

Figure 4.11 illustrates an example of the operation of an AC under the continuous mode, Mode 1, Mode 2 and Mode 3 over a period of 24 hours for a lounge room. The flow chart of the implementation of the methodology described here is given in

Figure 4.10: Sample of actual monthly energy consumption for one of the houses

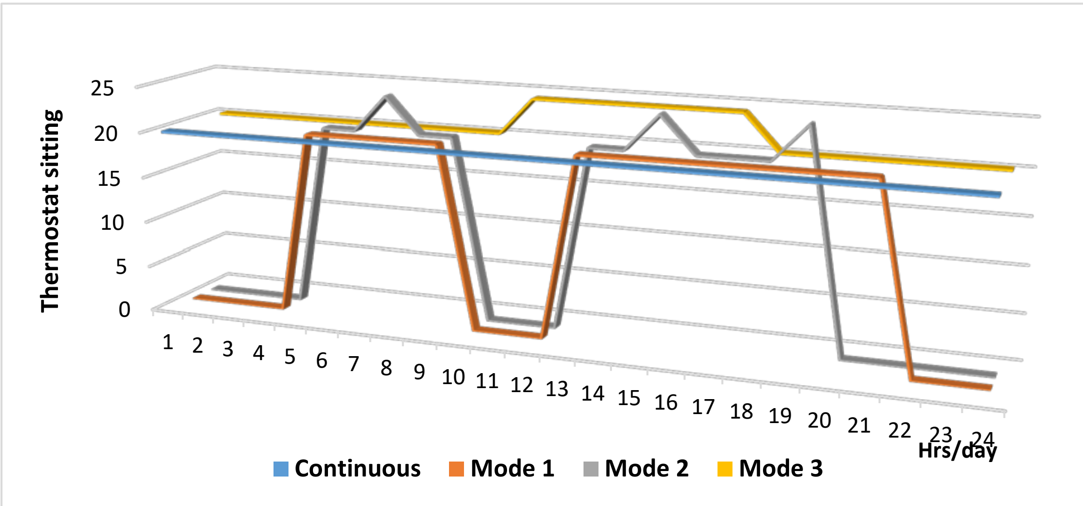


Figure 4.11: Example of the continuous mode, Mode 1 , Mode 2 and Mode 3 over a period of 24 hours for a lounge room

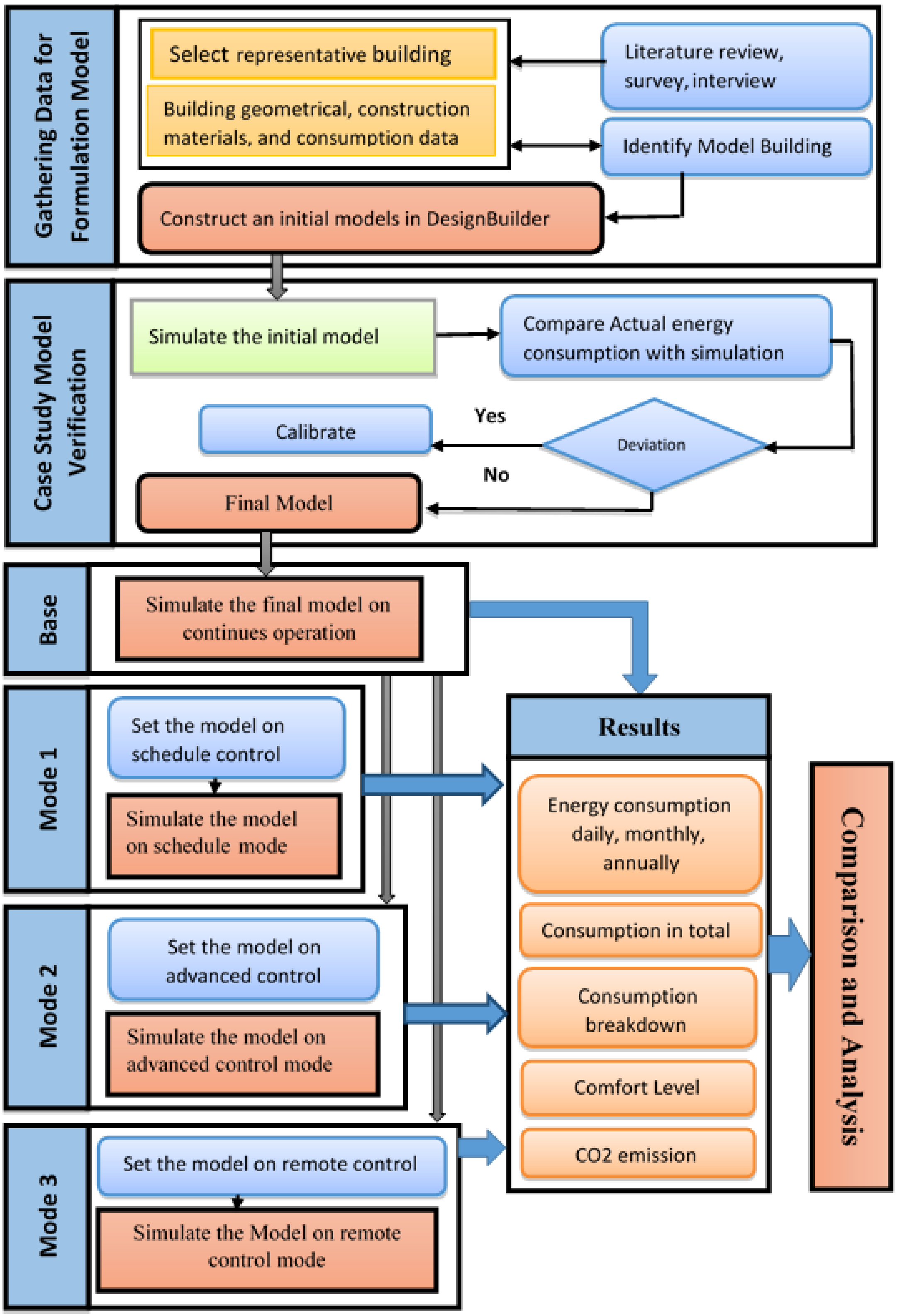


Figure 4.12: The flow chart of the methodology

4.5.4 Results

In this section, the results of the computer simulation will be presented. For each house in the case study, as previously mentioned, the parameters which DesignBuilder used for computing the simulation values include the plan of the house describing its physical geometry, its orientation and physical location (latitude and longitude), the parameters of the building materials as well as the real hourly weather pattern for the defined location, and so on. Full details of the simulation results are given in Appendix C. Firstly, the models are simulated and analysed for different thermostat settings. In order to determine the thermostat setting that best reflect the actual energy consumption of the chosen representative buildings, the actual measured values of energy consumption are compared with the results obtained through simulation in order to check that the model is representative of the actual buildings. The energy consumption within the studied residential buildings was calculated for daily, weekly, monthly and yearly energy consumption. Once the thermostat setting is determined, this value is used as the baseline value for the simulation of the residential buildings installed with ACs for different modes of operation. Thereafter, the results of the different modes of operations of the ACs where analysed and compared with the baseline (i.e. the case of the ACs being continuously operated with constant thermostat settings throughout the summer) in order to determine the energy consumption savings that are possible.

4.5.4.1 House 1: A floor in a two-storey building

Having defined the parameters of the houses to the DesignBuilder software, Figure 4.13 shows the actual reading and the simulated results for the single floor in a two-storey building (House 1). For the simulation results, two thermostat settings were tested: DesignBuilder was used to simulate House 1 with thermostat setting of 18^{o}C and it was also used to simulate the house with thermostat setting of 20^{o}C – recall that 18^{o}C and 20^{o}C were the range which 63% of the survey respondents mentioned that they set their thermostat to during the summer months. From the results of these simulations (refer to Figure 4.13), it is clear that 20^{o}C setting is closer to the actual measured value that was actually taken for House 1 during this study; thus, the value of 20^{o}C will be taken as the typical value of thermostat settings in subsequent simulations. Also, it is important to note that the computer simulation was able to capture the significant increase in the energy consumption from May to September – which is primarily due to the use of the AC during this period. Figure 4.14 shows the correlation plot of the two variables: the energy consumption obtained by simulation and the energy consumption obtained by direct measurement. The value of 0.92 of the statistical coefficient of determination, R^2, for the correlation plot indicates that the predictions from simulation highly fit the data from the actual measurement.

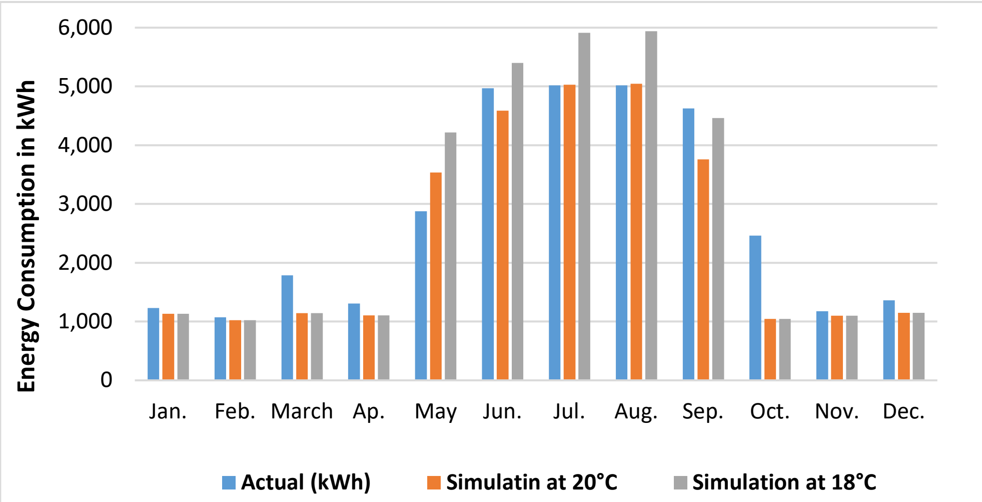


Figure 4.13: The actual reading and simulation results of the monthly energy consumption of House 1 with the AC working on continuous mode at thermostat settings of 18°C and 20°C

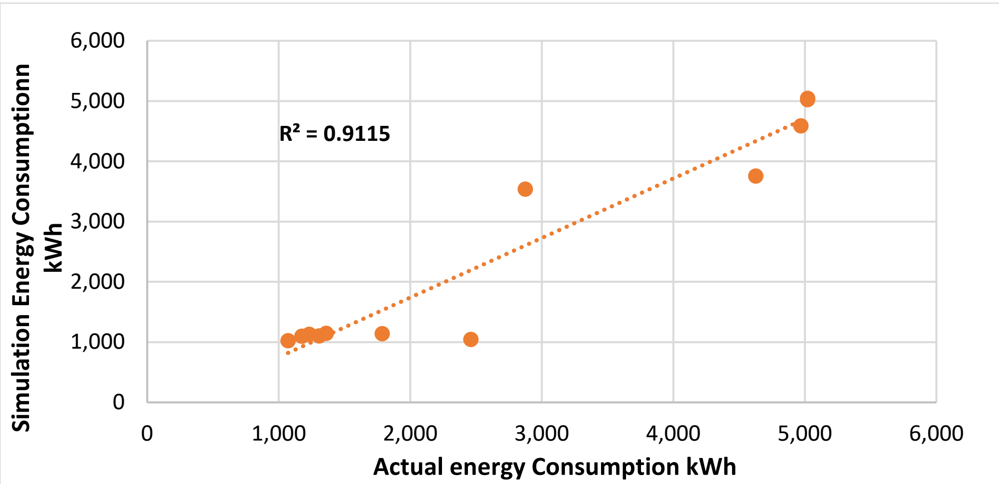


Figure 4.14: The correlation plot of the two variables: the monthly energy consumption of house 1 obtained by simulation with the AC working on continuous mode at thermostat setting on 20°C and the energy consumption obtained from monthly bills

To give an idea of the energy consumption savings possible, Figure 4.15 shows a comparison of the actual readings and as well as the results of the simulation with thermostat setting to 20^{o}C and working on continuous mode, Mode 1 (scheduled mode) and Mode 2 (advanced control mode) operation of the air conditioning systems for House 1. For Mode 1, each room of the house has its own schedule: the ACs in the bedrooms are set to turn ON from 6:00 pm to 6:00 am and from 1:00 pm to 2:00 pm, the AC in the lounge is set to switch OFF only between 9:00 am and 11:00 am and from 11:00 pm to 6:00 am, the AC in the guest room runs from 1:00 pm to 3:00 pm then from 6:pm to 11:00 pm but for only two days a week and the AC for the dining room is switched ON from 6:00 am to 9:00 am, from 12:00 noon to 3:00 pm and from 7:00 pm to 9:00 pm. For Mode 2, the thermostat settings for the AC are the same with Mode 1 except that the ACs' settings are changed from 20°C setting to 24°C setting when it is supposed to be turned ON and the room is unoccupied. All these settings are motivated from the results of the survey conducted in this study in relation to AC usage and customer behaviour in KSA (refer to the Appendix B). The results show that Mode 2 operation has minimum energy consumption followed by Mode 1, and the simulation of the continuous mode closely matches what was obtained from measurement (actual household bill) for House 1.

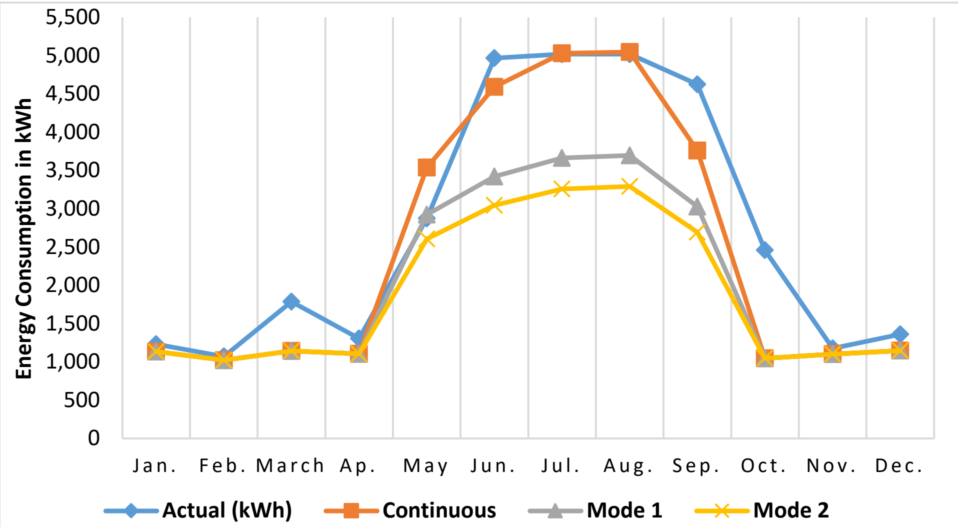
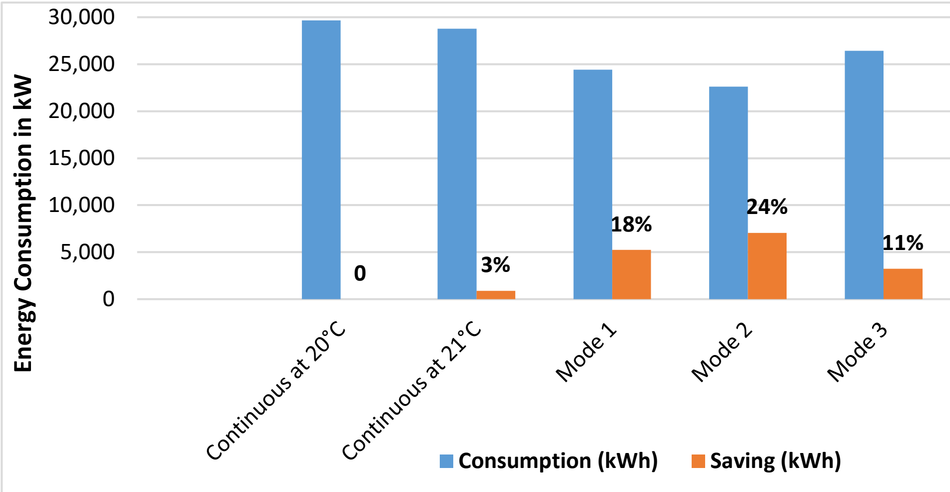


Figure 4.15: Actual readings and simulation results of energy consumption with thermostat setting to 20 °C under different AC operation modes for House 1

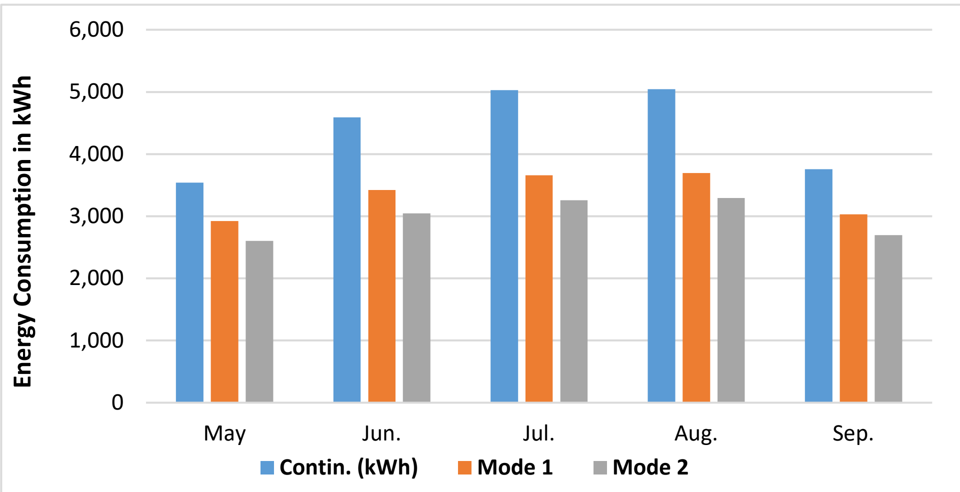
For the next simulation, the simulation runs over the period of one year, firstly, without schedule (i.e. continuous operation), and then under schedule (Mode 1) with different values of thermostat settings (20°C, 21°C and 24°C). The difference between the simulation results was used to deduce the energy savings due to the use of the scheduled mode of control. The advanced control mode (Mode 2) which depends on occupancy and remotely controlled mode (Mode 3 – where the utility company remotely set all ACs thermostats to 24°C) were also simulated. Table 4.7 and Figure 4.19a show the results of the annual energy consumption simulation, including the energy savings over one year. Table 4.8 and Figure 4.19b indicated the results of the five summer months. This is also true for all subsequent simulations related to House 2, the villa and the flat.

Table 4.7: Annual energy consumption under the continuous and different modes of AC operation for House 1.

AC system Operation Method	Annual Consumption (kWh)	Saving (kWh)	Annual Saving (%)
Continuous at 20 °C	29,661	0	0
Continuous at 21 °C	28,770	891	3%
Mode 1	24,430	5231	18%
Mode 2	22,598	7063	24%
Mode 3	26,417	3244	11%



(a)



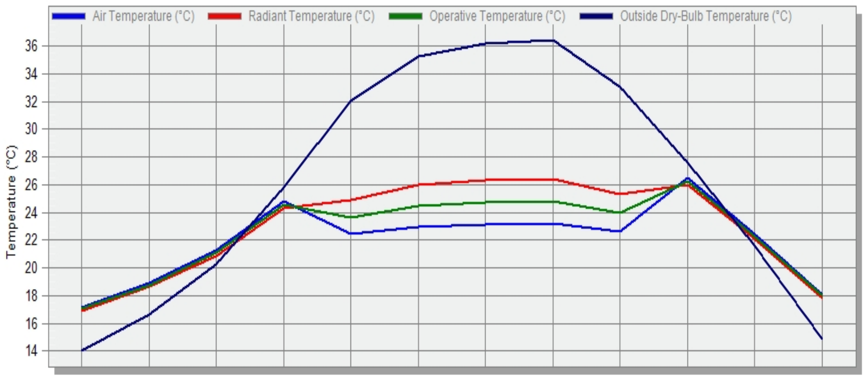
(b)

Figure 4.16: Simulation results of energy consumption at 20 °C thermostat setting under continuous mode, Mode 1 and Mode 2 operation of the air-conditioning systems for House 1: (a) Annual Consumption; (b) Consumption during the summer months.

Table 4.8: Monthly energy consumption under the continuous and different modes of AC operation for House 1 during the summer.

Months	Continue (kWh)	Mode1 (kWh)	Mode2 (kWh)	Mode 3 (kWh)	Mode 1 Saving (%)	Mode 2 Saving (%)	Mode 3 Saving (%)
May	3,538	2,922	2,605	3,913	17%	26%	16%
Jun.	4,590	3,423	3,046	3,695	25%	34%	19%
Jul.	5,028	3,661	3,259	4,023	27%	35%	20%
Aug.	5,046	3,696	3,292	4,047	27%	35%	19.%
Sep.	3,757	3,028	2,695	2,,998	19%	28%	20%

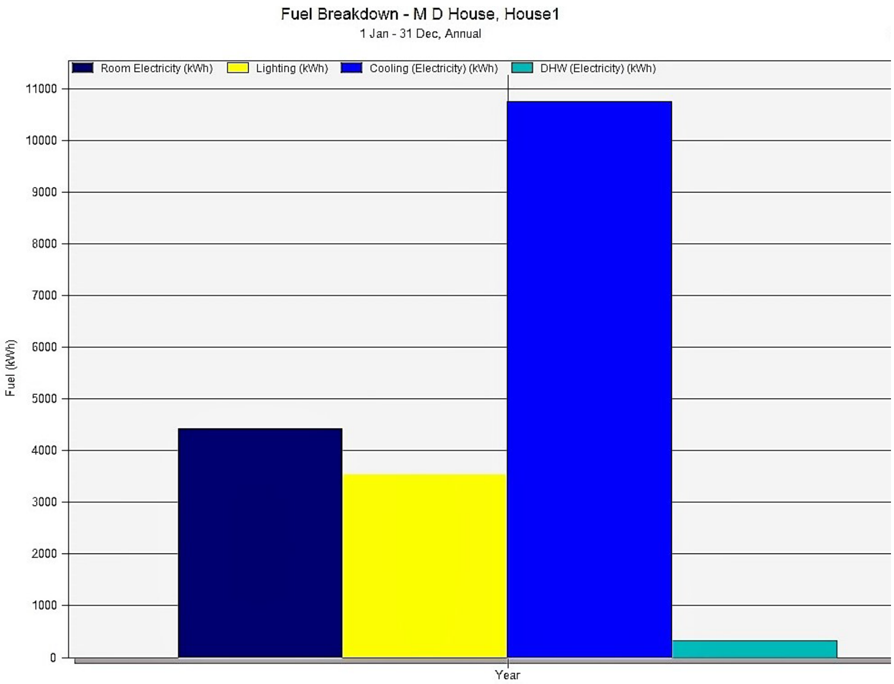
Figure 4.17 shows the results of the simulation of the comfort level of House 1 over the period of one year using Mode 1of the ACs' operation during summer months. The comfort level is measured by the levels of air temperature, radiant temperature, operative temperature, outside dry-bulb temperature and percentage relative humidity. From the plots on the figure, it can be observed that as the outside temperature begins to rise above 25^{o}C at the end of March, the system clearly achieves its aim of maintaining the indoor operative temperature between 21^{o}C and 25^{o}C until the end of September.



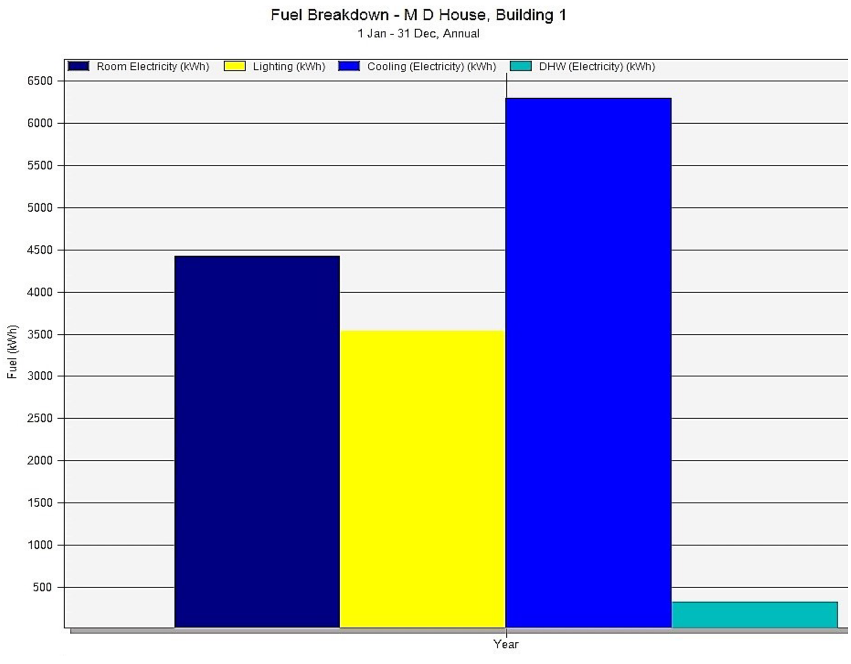
Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air Temperature (°C)	17.17	18.95	21.29	24.82	22.42	23.00	23.15	23.20	22.65	26.46	22.49	18.11
Radiant Temperature (°C)	16.91	18.64	20.89	24.33	24.90	26.03	26.33	26.40	25.33	25.98	22.08	17.83
Operative Temperature (°C)	17.04	18.79	21.09	24.57	23.66	24.51	24.74	24.80	23.99	26.22	22.28	17.97
Outside Dry-Bulb Temperature (°C)	14.03	16.67	20.28	25.86	32.05	35.24	36.21	36.44	33.04	27.59	21.57	14.92
Relative Humidity (%)	36.37	30.85	30.06	26.26	28.55	28.02	21.25	24.70	31.18	24.12	24.47	47.59

Figure 4.17: The comfort level of House 1 over a period of one year

A breakdown (which includes the consumption for the rooms, lighting, cooling and direct hot water) of one month (August) energy consumption for continuous mode and for Mode 1 operation of the AC for House 1 is shown in Figure 4.18. In Figure 4.18, the energy consumption due to cooling reduces from approximately 12,800 kWh of the continuous mode case to 7,200 kWh of the Mode 1 case. Figure 4.19 is shows the electricity consumption of House 1 on a typical day during the summer (4 July) under continuous mode and Mode 1 operation of AC. The average daily and maximum energy consumptions reduce noticeably for the Mode 1 operation compared to the continuous AC operation mode.

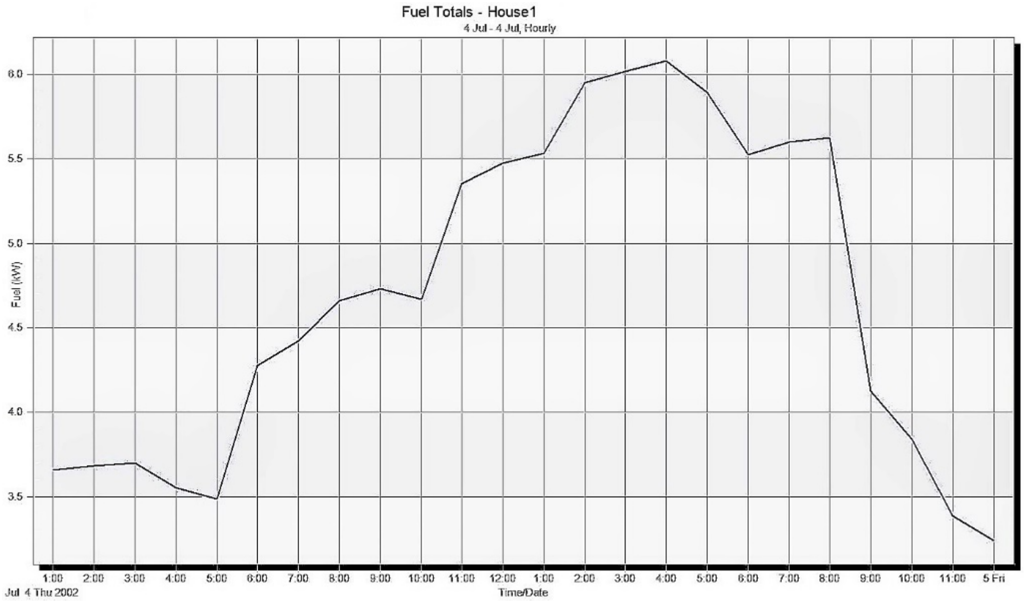


(a)

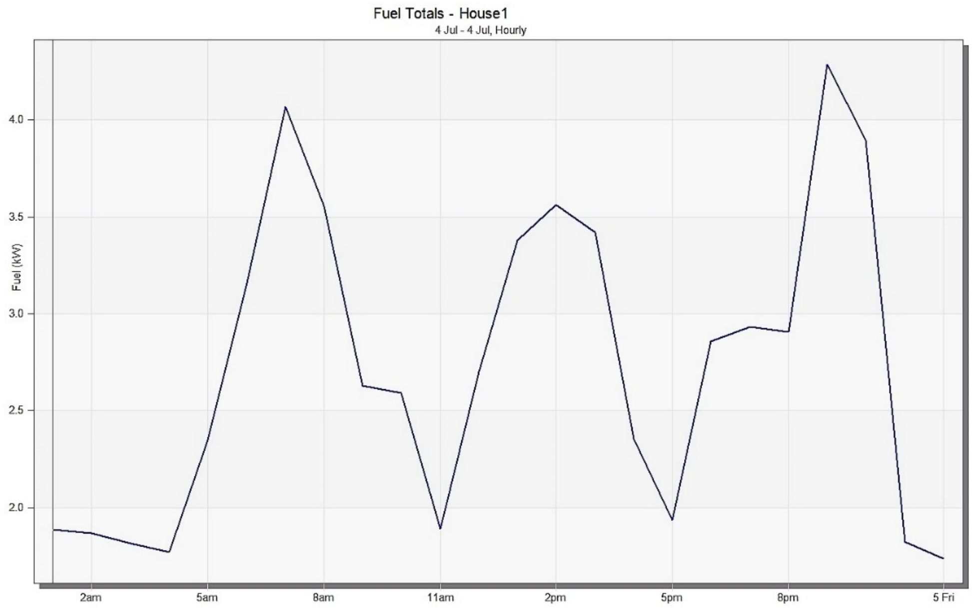


(b)

Figure 4.18: A breakdown of the annual energy consumption for continuous mode (a) and for Mode 1 (b) operation of the AC for House 1



(a)



(b)

Figure 4.19: The simulation of electricity consumption of House 1 on a typical summer day (4 July) under (a) continuous mode and (b) Mode 1 operation of AC

For comparison with House 1, the results of the simulation of the continuous air conditioning system operation and Mode 1 and Mode 2 air conditioning system operations for House 2, the Villa and the Flat are given in Table 4.9, Table 4.11 and Table 4.13, respectively. Also, monthly actual readings and simulation results of energy consumption with thermostat setting to 20°C under continuous mode, Mode 1 and Mode 2 operation of the air conditioning systems for House 2, the Villa and the Flat are given in Figure 4.20, Figure 4.23 and Figure 4.26. Figure 4.21, Figure 4.24 and Figure 4.27 explore the annual and summer months' simulation results of energy consumption at 20°C thermostat setting under different AC operation modes, while Figure 4.22, Figure 4.25 and Figure 4.28 show the electricity consumption of House 2, the Villa and the Flat on a typical summer day (4 July) under continuous mode and under Mode 1 operation of the AC.

4.5.4.2 Energy consumption at House 2 (traditional house)

Table 4.9: Annual energy consumption under the continuous and different modes of AC operation for House 2.

AC system Operation Method	Consumption (kWh)	Saving (kWh)	Annual Saving (%)
Continuous at 20 °C	39,355	0	0
Continuous at 21 °C	38,291	1,064	3%
Mode 1	27,314	1,2040	31%
Mode 2	24,885	1,4469	37%
Mode 3	34,989	4,366	11%

Table 4.10: Monthly energy consumption under the continuous and different modes of AC operation for House 2 during the summer.

Month	Simulation (kWh)	Mode 1 (kWh)	Mode 2 (kWh)	Mode 3 (kWh)	Mode 1 Saving (%)	Mode 2 Saving (%)	Mode 3 Saving (%)
May	5,918	3,974	3,537	4,853	33%	40%	18%
Jun.	6,974	4,496	4,002	5,614	36%	43%	19%
Jul.	7,320	4,849	4,316	5,856	34%	41%	20.%
Aug.	7,568	4,675	4,161	6,069	38%	45%	19%
Sep	5,036	6,343	4,087	4,089	36%	42%	18%

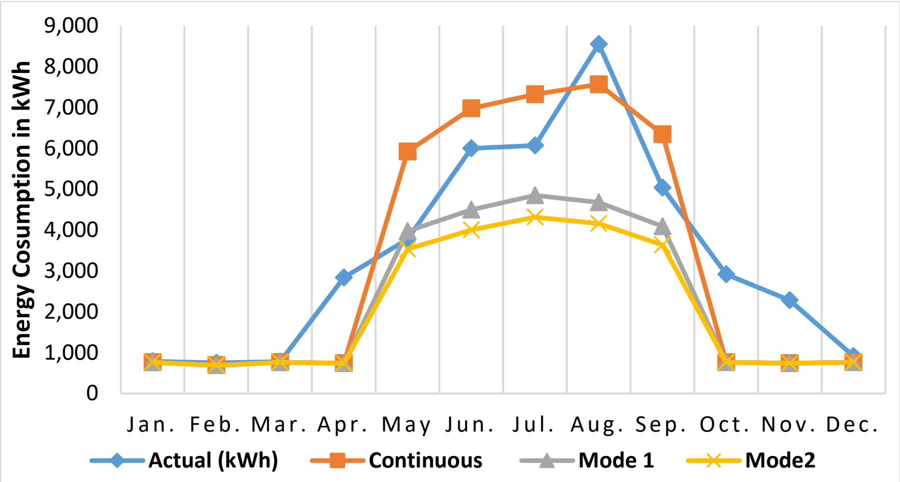
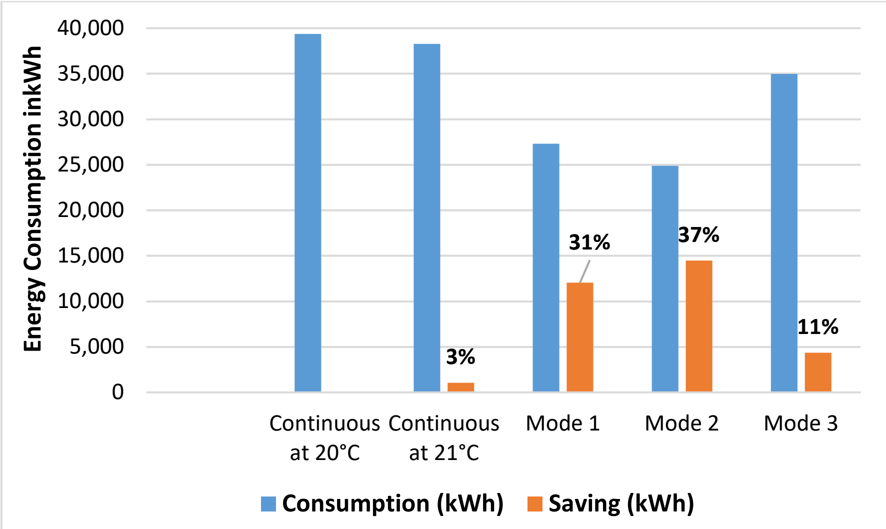
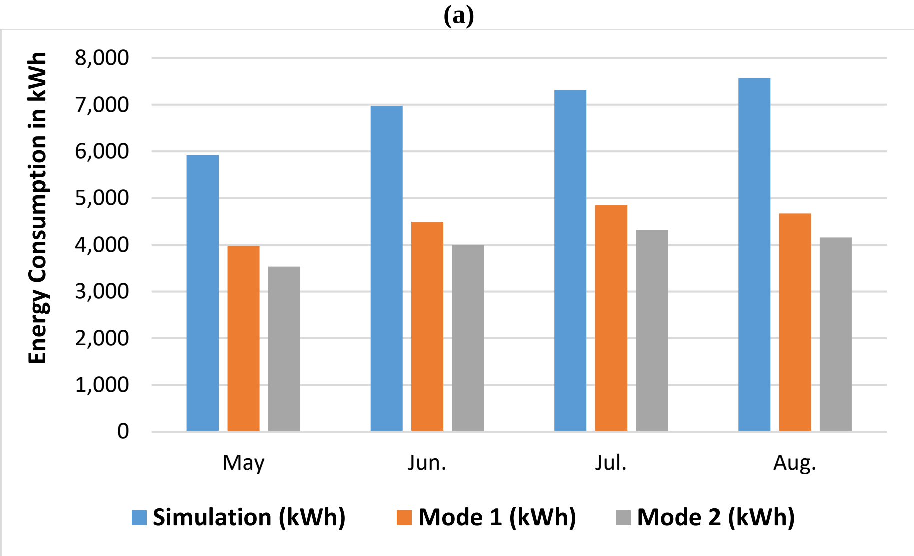


Figure 4.20: Actual readings and simulation results of energy consumption with thermostat setting to 20 °C under different AC operation modes for House 2

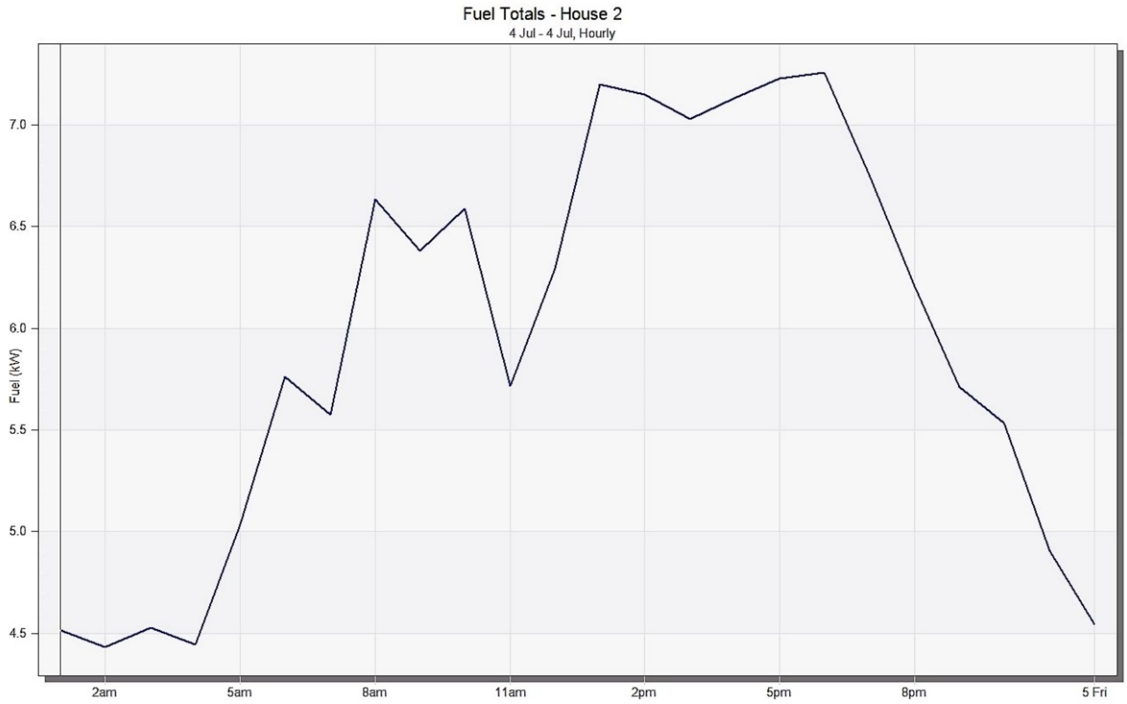


(a)

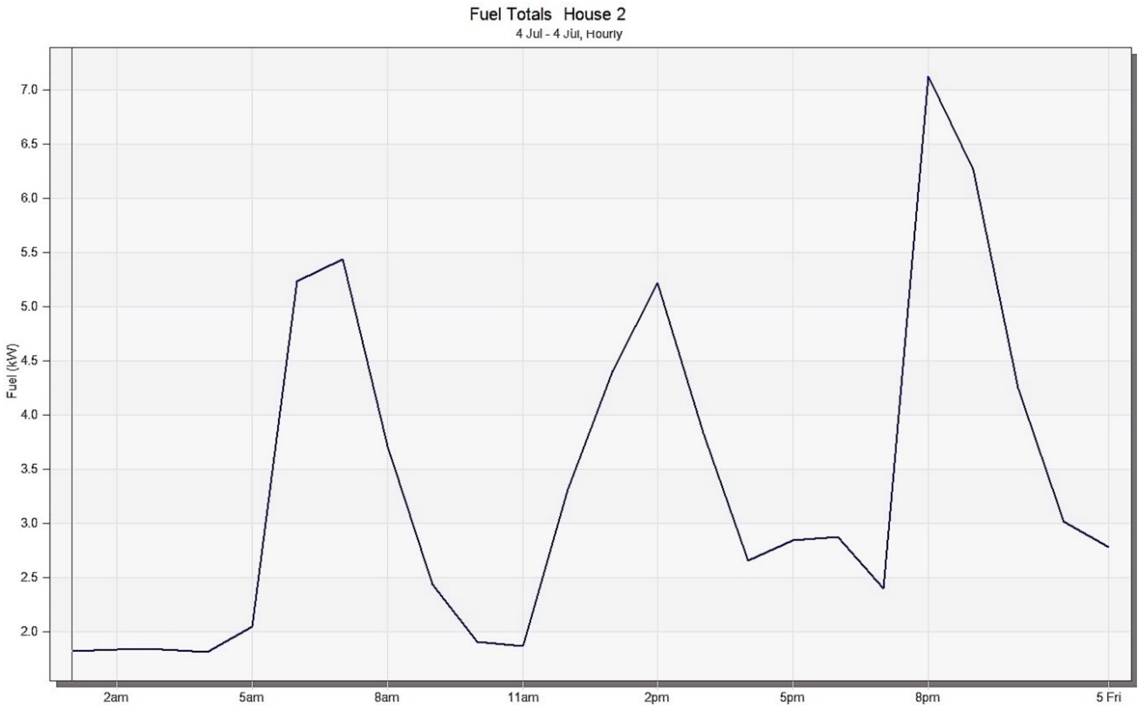


(b)

Figure 4.21: Simulation results of energy consumption at 20 °C thermostat setting under continuous mode, Mode 1 and Mode 2 operation of the air-conditioning systems for House 2: (a)Annual Consumption; (b) Consumption during the summer months.



(a)



(b)

Figure 4.22: The simulation of electricity consumption of House 2 on a typical summer day (4 July) under (a) continuous mode and (b) Mode 1 operation of AC

4.5.4.3 Energy consumption at the Villa

Table 4.11: Annual energy consumption under the continuous and different modes of AC operation for the Villa.

AC Operation Method	Consumption (kWh)	Saving (kWh)	Annual saving (%)
Continuous	67,277	0	0
Mode 1	57,368	9,908	15%
Mode 2	52,786	14,490	22%
Mode 3	61,219	6,058	9%

Table 4.12: Monthly energy consumption under the continuous and different modes of AC operation for Villa during the summer.

Month	Simulation (kWh)	Mode 1 (kWh)	Mode 2 (kWh)	Mode 3 (kWh)	Mode 1 Saving (%)	Mode 2 Saving (%)	Mode 3 Saving (%)
May	7,647	5,879	4,997	6,347	23%	35%	17%
Jun.	8,608	6,585	5,597	7,016	24%	35%	18%
Jul.	9,035	6,905	5,870	7,246	24%	35%	20%
Aug.	9,315	7,124	6,056	7,452	24%	35%	20%
Sep.	7,879	6,083	5,474	6,240	23%	31%	21%

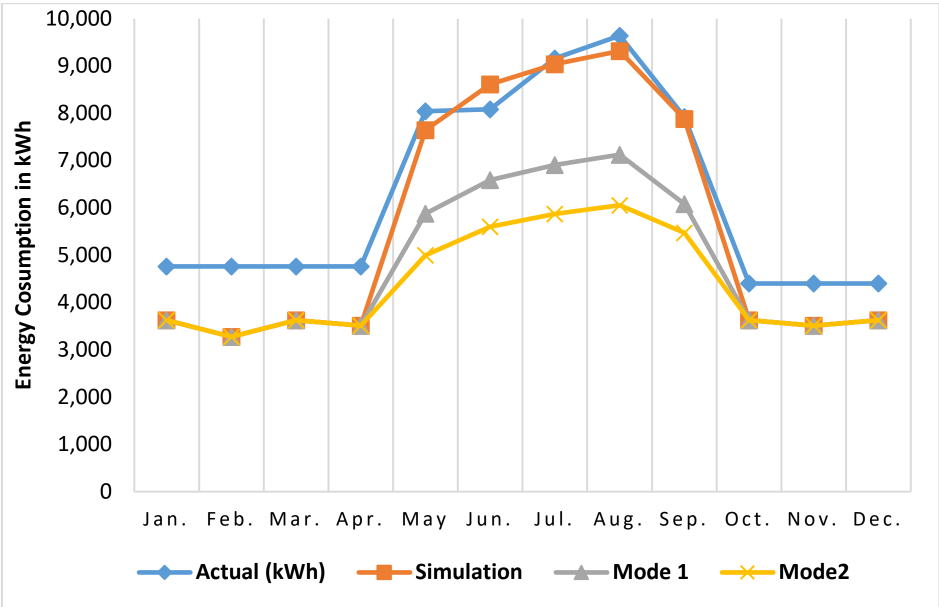
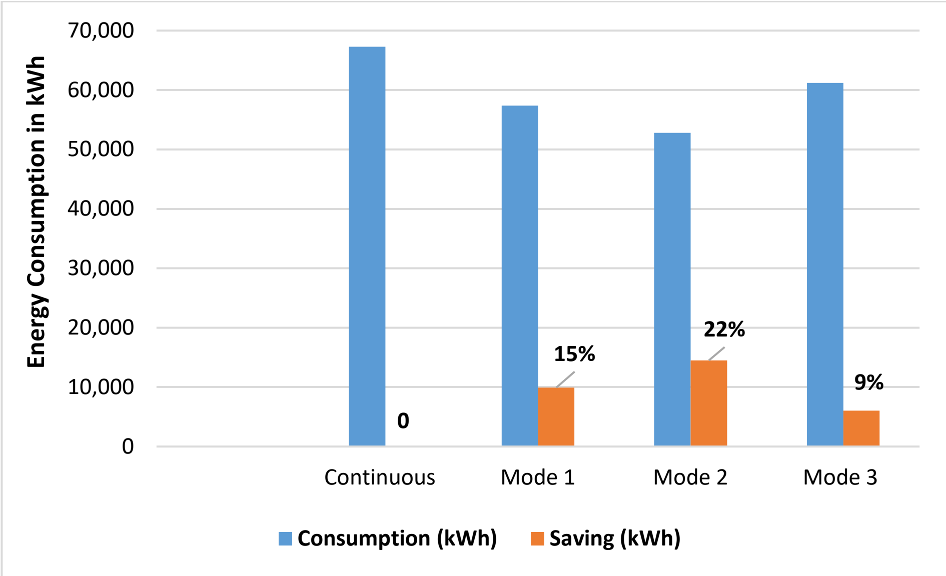
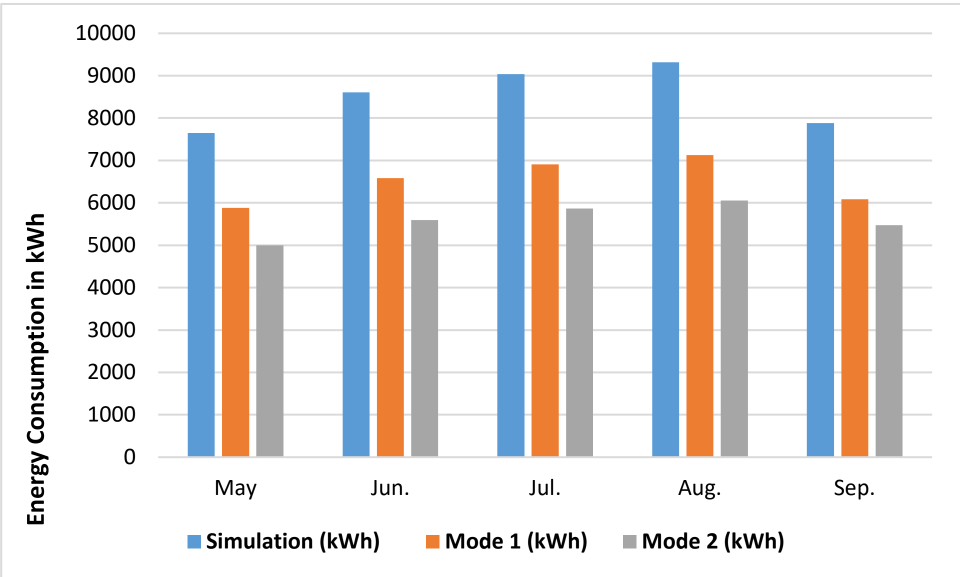


Figure 4.23: Actual readings and simulation results of energy consumption with thermostat setting to 20 °C under different AC operation modes for Villa

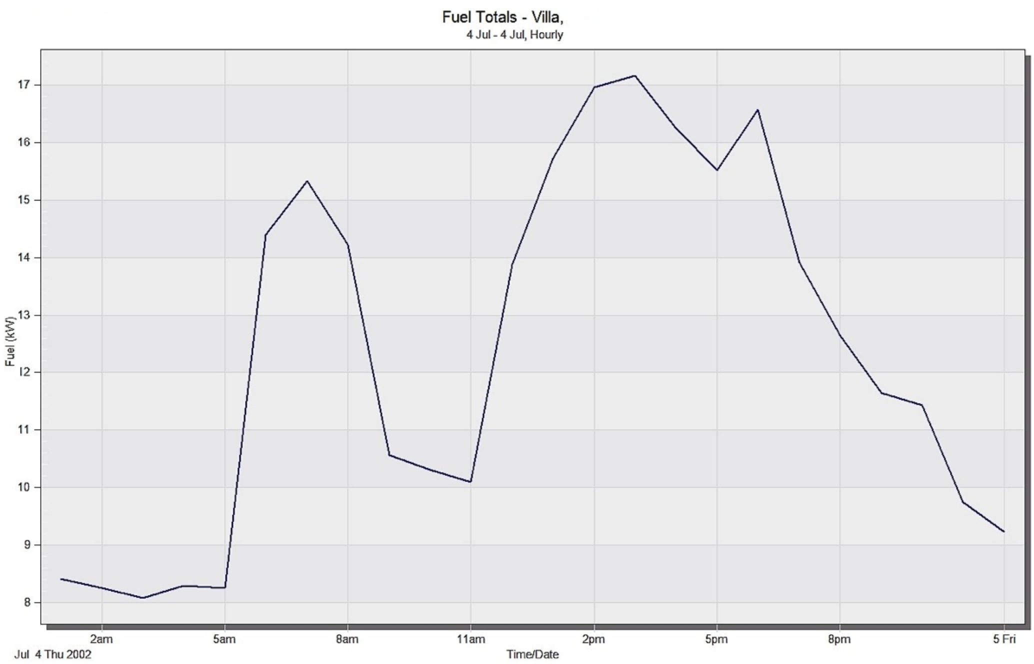


(a)

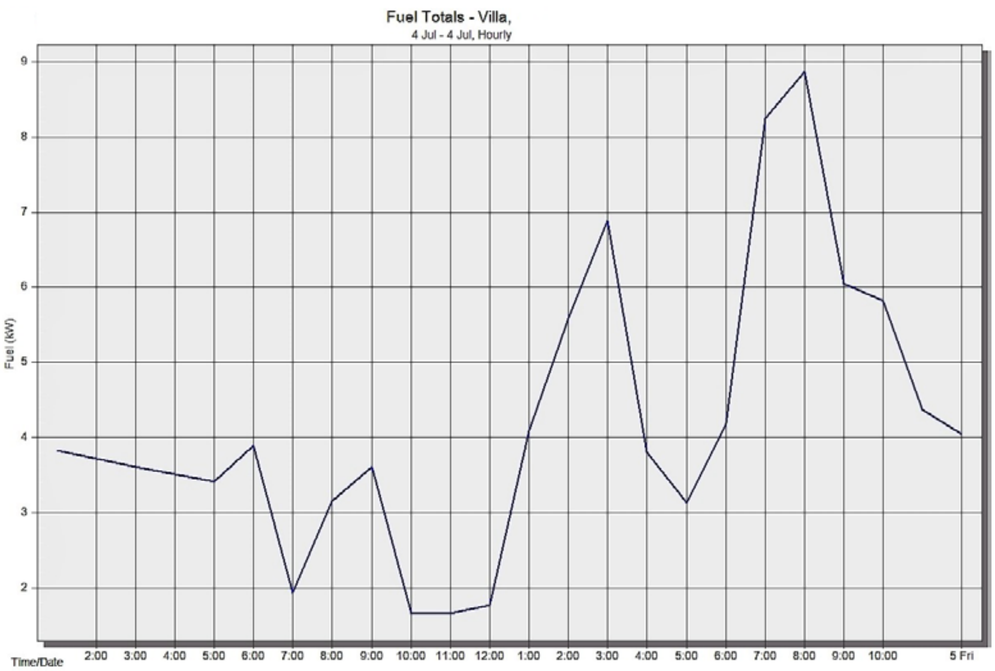


(b)

Figure 4.24: Simulation results of energy consumption at 20 °C thermostat setting under continuous mode, Mode 1 and Mode 2 operation of the air-conditioning systems for Villa: (a) Annual Consumption; (b) Consumption during the summer months



(a)



(b)

Figure 4.25: The Simulation of the electricity consumption of the villa on a typical summer day (4 July) under (a) continuous mode and (b) Mode 1 operation of AC

4.5.4.4 Energy consumption at the Flat

Table 4.13: Annual energy consumption under the continuous and different modes of AC operation for the Flat.

AC Operation Method	Consumption (kWh)	Saving (kWh)	Annual Saving (%)
Continuous	25,180	0	0
Mode 1	19,028	6,152	24%
Mode 2	18,168	7,012	28%
Mode 3	21,759	3,421	14%

Table 4.14: Monthly energy consumption under the continuous and different modes of AC operation for Flat during the summer.

Month	Simulation (kWh)	Mode 1 (kWh)	Mode 2 (kWh)	Mode 3 (kWh)	Mode 1 Saving (%)	Mode 2 Saving (%)	Mode 3 Saving (%)
May	3,530	2,362	2,128	2,852	33%	40%	19%
Jun.	3,713	2,492	2,280	2,896	33%	39%	22%
Jul.	3,909	2,620	2,490	3,010	33%	36%	23%
Aug.	3,942	2,640	2,479	3,000	33%	37%	23%
Sep.	3,544	2,372	2,249	2,694	33%	37%	20%

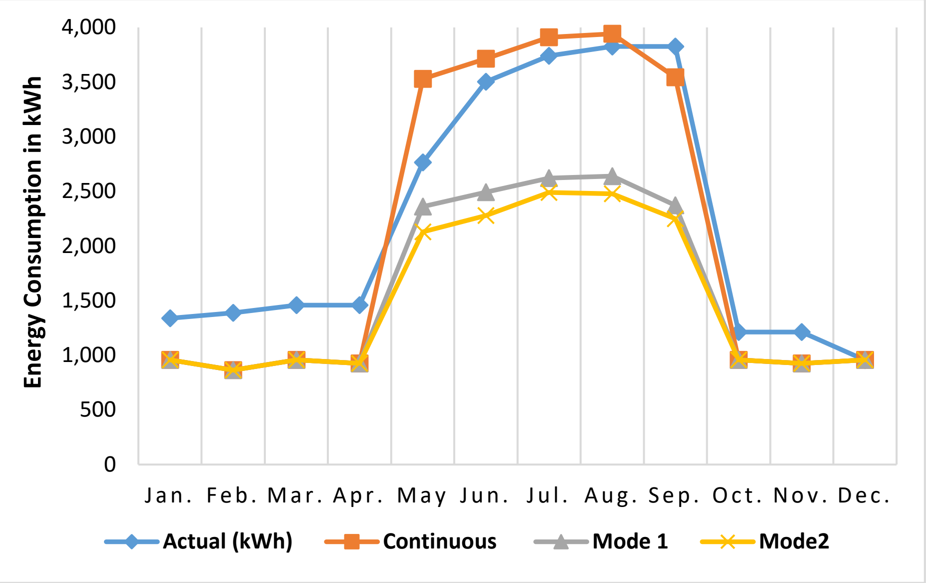
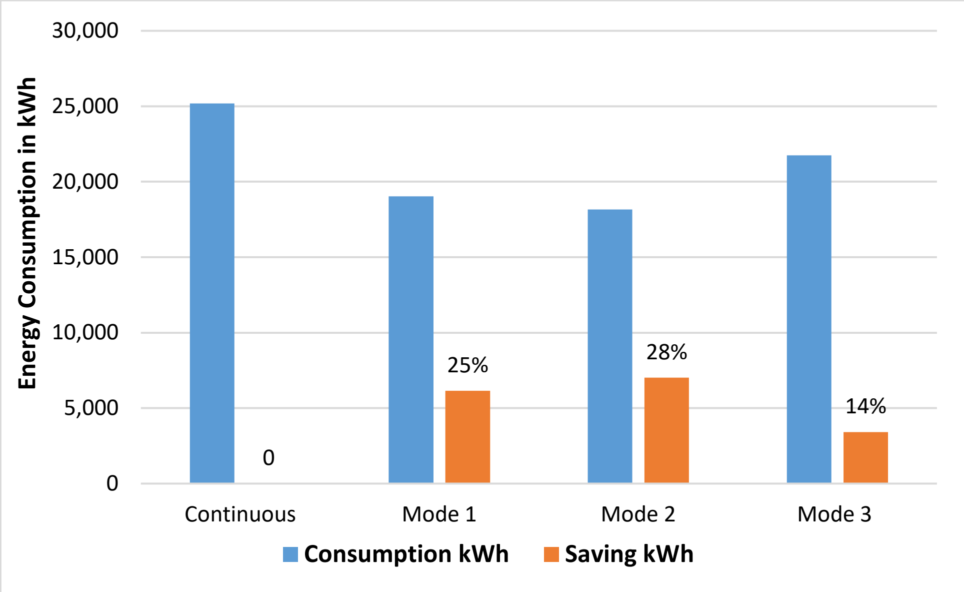
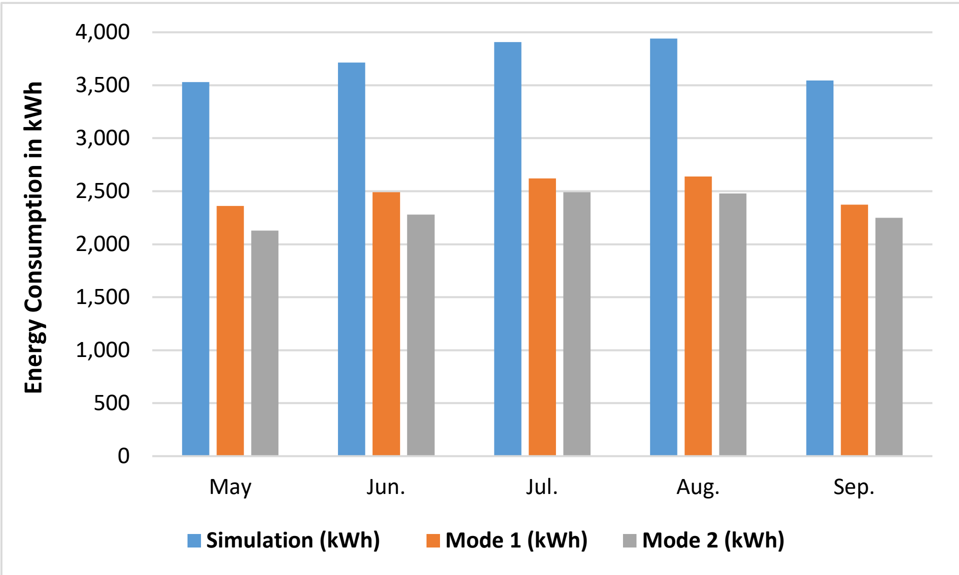


Figure 4.26: Actual readings and simulation results of energy consumption with thermostat setting to 20 °C under different AC operation modes for Flat

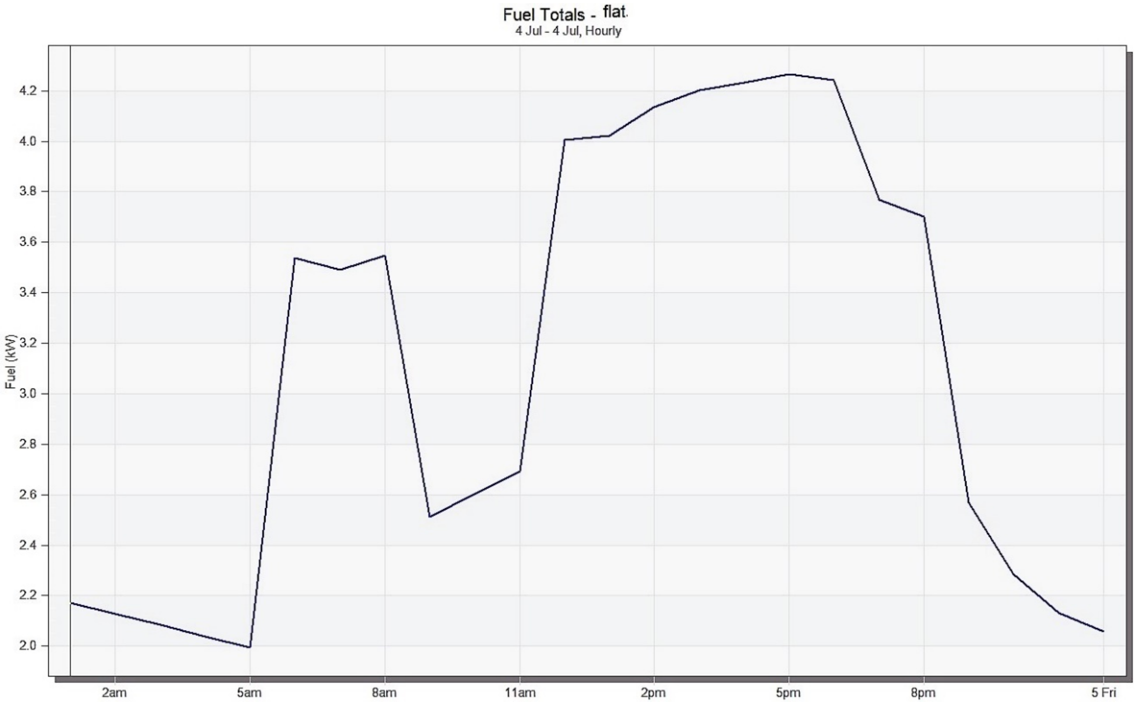


(a)

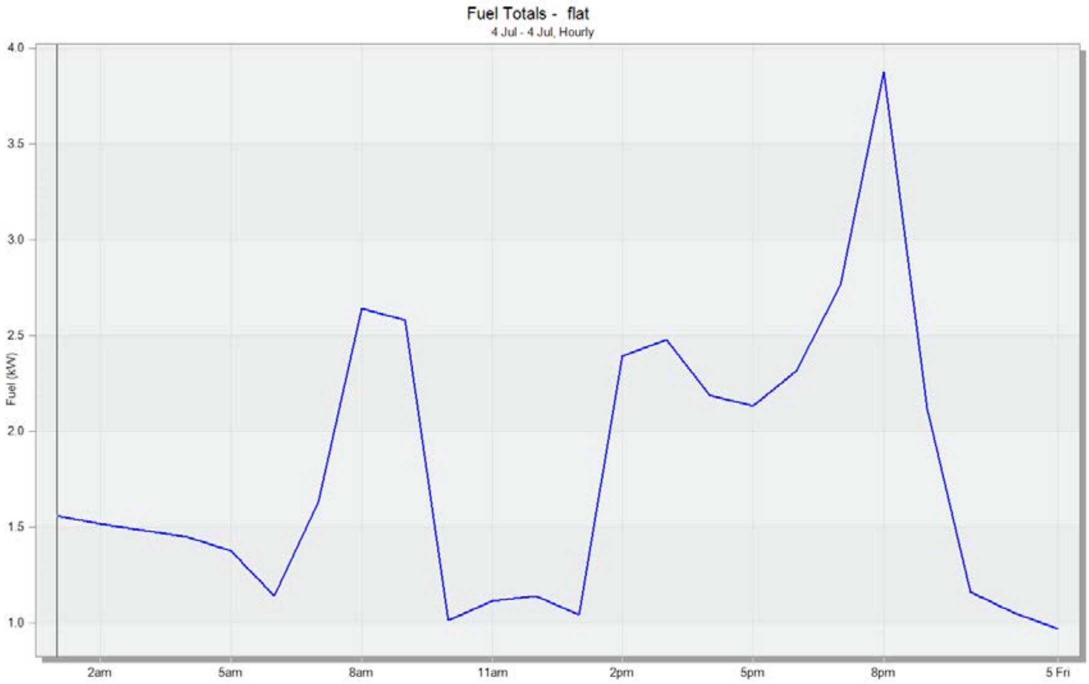


(b)

Figure 4.27: Simulation results of energy consumption at 20 °C thermostat setting under continuous mode, Mode 1 and Mode 2 operation of the air-conditioning systems for Flat: (a) Annual Consumption; (b) Consumption during the summer months



(a)



(b)

Figure 4.28: Simulation electricity consumption of Flat on a typical summer day (4 July) under (a) continuous mode and (b) Mode 1 operation of AC

4.5.5 Discussions

The simulation results of the annual electricity consumption and saving for each studied building was analysed. The results of the preceding section can be summarized as follows:

- For House 1, House 2, the Villa and the Flat, the yearly savings achieved through Mode 1 are 18%, 31%, 15% and 25%, respectively.
- For House 1, House 2, the Villa and the Flat, the yearly savings achieved through Mode 2 are 24%, 37%, 22% and 29%, respectively.
- For House 1, House 2, the Villa and the Flat, the yearly savings achieved through Mode 3 are 11%, 11%, 9% and 13%, respectively.

Herein, only the annual savings have been given. For the five summer months, the savings ranges from 16% to 35% for House 1, 18% to 45% for House 2, 17% to 35% for the Villa, and 19% to 40% for the Flat depending on the mode of operation of the AC.

During the peak hour (2:00 pm – 3:00 pm), the maximum power consumption for each of the four houses with each of the operational modes of ACs is given in Table 4.15. Using data of the number of each type of house in Riyadh, Table 4.16 shows the corresponding savings for each house type category and the total savings for the Riyadh region during the peak hour.

Table 4.15: The energy consumption for each category of house on different AC operations modes during the peak hour

AC Operation Mode	House 1 (kW)	House 2 (kW)	Villa (kW)	Flat (kW)
Continuous Mode	6.3	7.5	17	4.5
Mode 1	3.4	5.9	6.2	2.6
Mode 2	2.85	3.6	5.65	1.9
Mode 3	5.22	5.8	14.61	3.91

Table 4.16: The total peak power and saving for each house type on different AC operations modes for the whole of Riyadh city

Dwelling's Name	AC Mode	Peak in (kW)	Number of dwelling	Total Consumption (kW)	Total saving (kW)	Saving (kW) for 30%
House 1	Continuous	6.3	127466	803036	0	0
	Mode 1	3.4	127466	433384	369651	110895
	Mode 2	2.85	127466	363278	439758	131927
	Mode 3	5.22	127466	665373	1376638	41299
House 2	Continuous	7.5	47596	356970	0	0
	Mode 1	5.9	47596	280816	76154	22846
	Mode 2	3.6	47596	171346	185624	55687
	Mode 3	5.8	47596	276057	80913	24274
Villa	Continuous	17	374900	6373300	0	0
	Mode 1	6.2	374900	2324380	4048920	1214676
	Mode 2	5.65	374900	2118185	425511	1276535
	Mode 3	14.61	374900	5477289	896011	268803
Flat	Continuous	4.5	279708	1258686	0	0
	Mode 1	2.6	279708	727241	531445	159434
	Mode 2	1.9	279708	531445	727241	218172
	Mode 3	3.91	279708	1093658	165028	49508

Accordingly, the total power needed for the whole of Riyadh during the peak-time hour is 20,329 MW (ECRA, 2015), From Table 4.16, the total power at peak time (i.e. 14:22) is 8,792 MW, which represents 43% of Riyadh peak power demand and it compares well with the residential portion (50% of total demand) as indicated in (ECRA, 2015). By applying the different AC operation modes, the values of total power savings for the whole of Riyadh are 5,026, 5,608, and 1,280 MW for Mode 1, Mode 2 and Mode 3, respectively during peak hour. These results are summarized in Table 4.17.

Assuming that only 30% of houses in Riyadh are willing to move to these solutions, the values of total peak demand reduction would be 1,508, 1,682 and 383 MW for Mode 1, Mode 2 and Mode 3, respectively, during the peak hour.

Table 4.17: The total peak power and saving of all houses types for the whole of Riyadh

AC Operation Mode	Total (MW)	Saving (MW)	Annual Saving (%)
Continuous Mode	8,792	0	0%
Mode 1	3,766	5,026	25%
Mode 2	3,184	5,608	28%
Mode 3	7,512	1,280	7%

It can be observed from Table 4.7, Table 4.9, Table 4.11 and Table 4.13 that the savings achieved with Mode 3 (the remote-control mode) gives the lowest energy savings. The savings achieved with Mode 2 (the advanced control mode) gave the best energy savings of 37%. For the individual houses, the results of Mode 2 operation mode is superior to what was reported in the literature that it is possible to achieve up to 33.6% energy savings using fixed monthly optimum thermostat setting (Al-Sanea & Zedan, 2008). In this study, it was not the optimum thermostat settings for each month that was used, rather, it was the scheduling of the thermostat setting (in the case of Mode 1 and Mode 2) and the use of DR (in the case of Mode 3) throughout the summer months that leads to better savings. In addition, another reason why the fixed monthly optimum thermostat setting described in (Al-Sanea & Zedan, 2008) is impractical is that it presumes that home occupants will be willing to re-set their thermostat to a new value monthly. As was previously observed in the survey results, up to 66% of the respondents rarely or never shut down their ACs during the summer months compared to 22% that usually do, and the remaining 12% fall between these two extremes. Moreover, it is unrealistic to expect that enough number of residents will manually turn off air conditioning systems (Sachs, 2004); this is also confirmed SEEC which often send reminders and requests that people in KSA should set their thermostat to 24^{o}C but their call is mostly always ignored (SEEC, 2017b). Thus, the Mode 1 and Mode 2 solutions that are proposed in this chapter allows the air-conditioning systems to run on a scheduled non-continuous basis; the sensors enable the smart thermostats to learn customers' occupancy behaviour over the periods of the day or week such that energy consumption is reduced during non-occupancy periods. The Mode 3 uses the DR approach where the utilities can automatically control the thermostat settings of the air conditioning systems of households if and when appropriate. Consequently, the approaches proposed in this chapter do not requiring daily thoughts or actions from occupants to achieve energy savings. Also, they are realistic and practical as they do not require home occupiers' intervention to change the thermostat settings.

4.6 Summary

In this chapter, potential solutions to the high energy demand associated with the use of air-conditioning systems in residential areas in KSA were presented. The main idea of the proposed solutions is reducing energy consumption due to the air conditioning systems by appropriate scheduling and controlling or by remote setting of the thermostat by the utilities while the comfort level of the building is set to an acceptable level. Using the DesignBuilder software, the results of three modes of operation of implementing the solutions for air conditioning systems show that the methods indeed reduced the energy consumption effectively and, in fact, the advance mode of operation – where the air conditioning is programmed based on typical house occupancy behaviour pattern obtained through survey and where the setting of the thermostat changes from a lower value when the room is occupied to higher value when a room in the house is not occupied for a short duration – is able to achieve up to 30% to 40% in terms of total annual energy savings depending on the house type. To achieve this level of saving however, the computer simulation assumes that the residential buildings are equipped with sensors which are able to detect occupancy with high degree of accuracy in order to obtain the schedule that can be updated periodically. Artificial intelligence techniques that combine sensor information with other data, such as mobile phone use, are an area of on-going research that could provide the required accuracy to realise these savings and future work should focus in this area.

Chapter 5: Solar Water Heating Systems

5.1 Introduction

Since water heating systems are important for domestic and industrial sectors, solar thermal systems, or solar water heating (SWH) systems, can be a better alternative as a source of hot water to the use of electric water heating systems in many countries where electric water heating systems are still dominant (Abd-ur-Rehman & Al-Sulaiman, 2016). Currently, the hot water generated from SWH systems finds use in domestic, commercial, and industrial sectors of the economy (Veeraboina & Ratnam, 2012). The SWH technology has gained applications ranging from their use for pool water heating and space heating to domestic water heating (Abd-ur-Rehman & Al-Sulaiman, 2016)**.**

The "first law" efficiency of solar to thermal energy conversion (with SWH systems) can reach up to 70% (Jaisankar *et al.*, 2011) which is much greater than the efficiency of solar to electricity conversion (i.e. solar PV systems) that is currently around 24.5% (Gul, Kotak & Muneer, 2016). SWH technology is both reliable and economical for hot water production (Chang *et al.*, 2009). The payback period for investment in SWH could be as small as 2-4 years depending on the type and size of the system. In the US, water heating accounts for 20% of all household energy use, and solar thermal production of hot water can lead to savings of up to 70-90% of the total water heating cost (Shukla *et al.*, 2013).

SWH systems are increasingly being used worldwide. The global trend of the solar thermal capacity and yield from 2000 to 2016 are given in Figure 5.1 (Weiss, Spörk-Dür & Mauthner, 2017). The deployment of SWH systems vary significantly from country to country. It is tempting to expect that developed countries with conducive climate will have higher installation of SWH systems than others. Figure 5.2 shows the total capacity of glazed water collectors in operation in kW per 1,000 inhabitants in 2014. It is clear that, a developed country like Australia, with huge solar energy resources, has little to show for harnessing solar energy resources via SWH systems. As another example, as of

2009, approximately 100,000 SWH systems are installed in the UK nationwide which represents only around 0.4% of the total UK housing units (Energy, 2008) but the figure has now increased to 250,000 as of 2014 (ESTIF, 2015). It is therefore, clear that factors such as policy, culture, and energy cost play a great role in the acceptance of SWH technologies (Leidl & Lubitz, 2009).

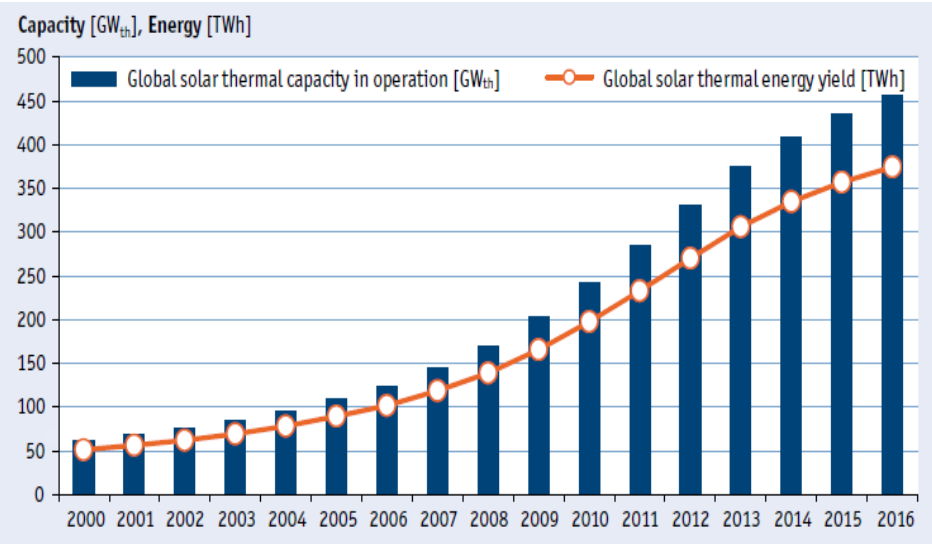


Figure 5.1: Global solar thermal capacity in operation and annual yields between 2000 to 2016 (Weiss, Spörk-Dür & Mauthner, 2017)

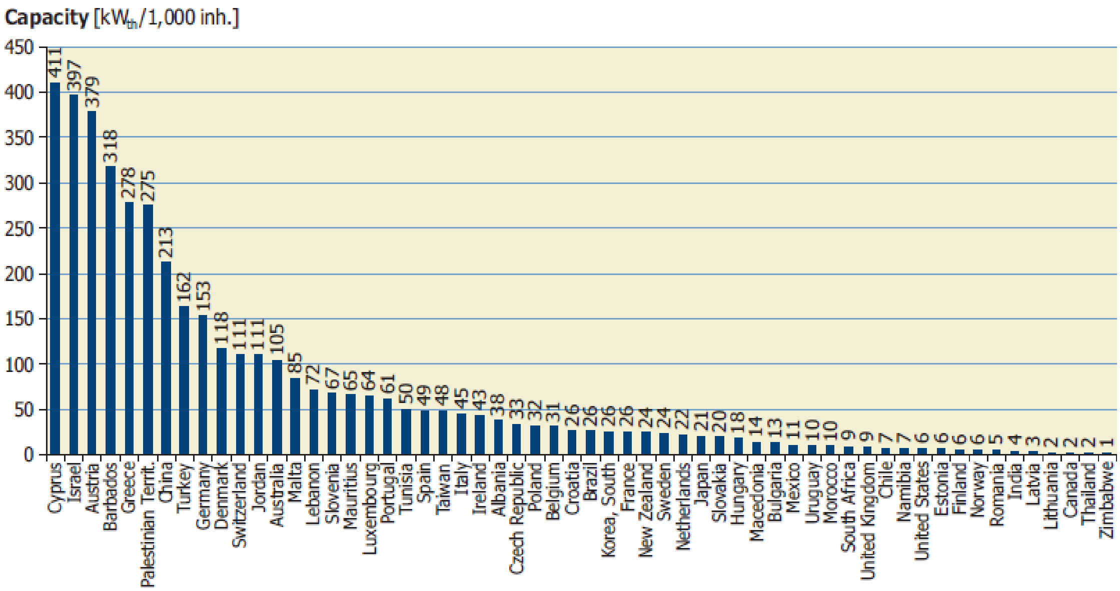


Figure 5.2: Total capacity of glazed water collectors in operation in kW per 1,000 inhabitants in 2014 (Franz Mauthner, Werner Weiss, 2016)

Over the past few decades, SWH systems have become one of the most cost-effective and popular renewable energy technologies (Godfrey & others, 2004). This chapter focuses on the reduction in peak electricity demand achievable when domestic hot water is supplied using SWH systems. A case study of Riyadh city in KSA is presented in particular to determine the electricity demand reduction that can be achieved from a large-scale deployment of SWH. This can encourage the government to popularize the use of SWH systems and decide how far to support an intervention (such as through initiating subsidy programs) that will encourage their usage. Factors influencing the volume of hot water consumption in KSA include climatic factors, human behaviour, house types, electricity consumption, and household income. This study also presents an estimate of hot water requirement for household with different number of members. While KSA has high potential for developing energy production via SWH systems, it has not been taking maximum advantage of this unique technology for increasing its energy generation and reducing peak electricity demand. The study includes new insights on the deployment of SWH in KSA and concluded that there is a useful potential benefit if the use of SWH systems in KSA can be increased.

The subsequent sections are arranged as follows: a summary of the working principle, components, and types of SWH systems is presented in Section 5.2. Background and reports on previous and on-going studies related to SWH systems in Section 5.3. The methodology used for studying the electricity savings achievable with the use of SWH systems in KSA, the modelling of hot water consumption and energy consumption as a result of hot water production, are presented in Sections 5.4 and 5.5, respectively. A case study of Riyadh city in KSA is presented in Section 5.6. The results and discussion of this study are summarized in Section 5.7. As the deployment of SWH systems is not without its challenges, a discussion on some of these challenges and recommendations based on the findings in the previous sections that are peculiar to KSA are also included in this section. Limitations of this study and chapter conclusion are presented in Sections 5.8 and 5.9, respectively.

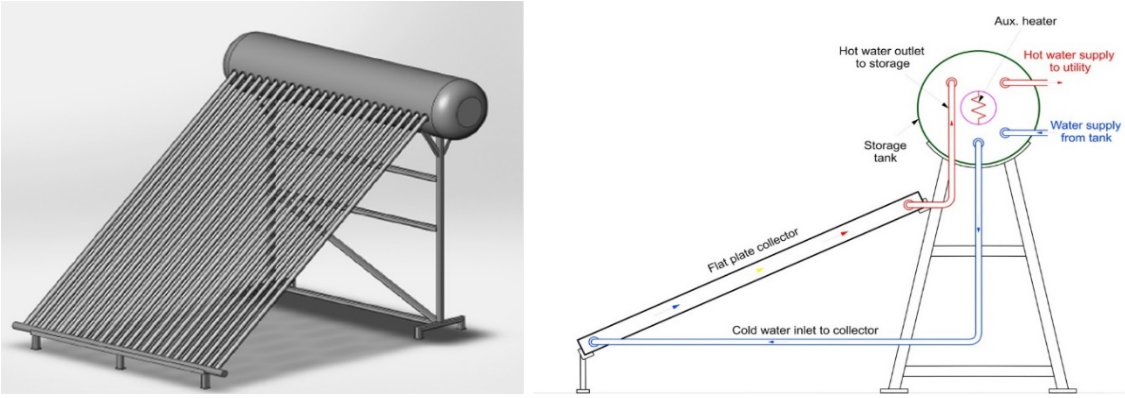
5.2 Working Principle, Components and Types of SWH Systems

5.2.1 Main Components of SWH systems

A SWH system consists of a solar energy collector, a storage tank and a working fluid to move heat energy to its point of storage. The working principle of solar thermal systems is based on the fundamentals of heat transfer through a solar collector (Abd-ur-Rehman & Al-Sulaiman, 2016)**.**

The description of the main components of SWH systems follows:

Collector**:** This is the main component of a SWH system and the system's efficiency is largely dependent on the performance of the collector. A primary heat exchanger converts solar energy into useful heat and uses a heat-transport fluid flowing through it to transfer the heat. The different types of solar collectors include flat-plate collectors, evacuated tube collectors, and compound parabolic concentrators, among others. While the flat-plate and the evacuated tube collectors are both widely used in solar thermal applications to provide relatively low to intermediate range of temperature (20°C to 200°C), the compound parabolic concentrators are particularly suitable for applications involving high temperatures (Venkatachalam & Solomon, 2018). The collectors of SWH systems are also often classified as glazed and unglazed collectors. In general, to minimize heat loss to the surrounding air, the glazed collectors have transparent upper sheets, and the backsides and edges are insulated. The unglazed collectors have no such protection from losses to ambient air, are therefore more susceptible to heat losses, and are less costly. Figure 5.3 shows a schematic of a flat-plate collector and an evacuated tube collector.



(a) **(b)**

Figure 5.3: Schematic diagram of (a) evacuated tube collector (Benli, 2016), and (b) flat-plate collector (Shrivastava, Kumar & Untawale, 2017)

***Storage*:** Due to diurnal (daytime) availability of sunshine, storage allows energy to be stored during sunshine for later use. Storage is achieved with insulated containers. Storage tanks are often constructed with steel but storage tanks built with other materials such as plastic and fibre glass also exist (Hossain *et al.*, 2011; Altuntop *et al.*, 2005). In order to reduce heat loss that is due to the mixing of hot and cold water associated with storage tanks, several designs and configuration are available.

Heat exchanger: This is commonly used as an optional component of a SWH system and connected to the inside of the storage tank to facilitate the exchange of heat between a working fluid and a storage fluid. In particular, heat exchangers are used in the indirect type of SWH systems to transfer the absorbed solar thermal energy in the form of heat from the working fluids to the storage tanks. There are various materials that are being used for manufacturing heat exchanges such as cast iron, aluminium, bronze, copper and so on, but copper is the most popular given its good thermal conductivity as well as its relatively good resistance to corrosion (Shukla *et al.*, 2013).

Heat transfer fluid: The heat transfer fluid (or working fluid) absorbs thermal energy from the collector and transmits the energy through the heat exchangers to the water in the storage tank. Factors that determine the working fluid's selection for a SWH system include properties of fluid such as its boiling point, freezing point, viscosity, thermal capacity and flashpoint. For instance, a fluid with high boiling point will be required in hot climates while that with a low freezing point will be needed in cold climates. Common heat transfer fluids include air, water, Glycol-water mixture, refrigerant liquids and hydrocarbon oils. Air and water are some of the most commonly used fluids although the water is often mixed with glycol additive to act as an anti-freeze (Shukla *et al.*, 2013). The systems shown in Figure 5.3 provide direct heating of the water used for sanitary purposes so cannot use a heat transfer fluid and are only appropriate where there is no risk of freezing.

Pump: This is commonly used for active types of SWH in order to develop hydraulic pressure for the circulation of the working fluid or water to increase heat transfer rate. A PV solar system can be used to power the pump (Bai & Fraisse, 2008).

Auxiliary heater: This is optional and provides means of heating up water externally during low- or non-availability of sufficient solar energy. It is also useful during periods when hot water demand cannot be met by a SWH system only.

5.2.2 Passive and Active SWH systems

SWH systems generally fall into two categories: passive and active systems.

Passive Systems: Passive SWH systems use heat driven convection to circulate the working fluid in the system. Passive SWH systems can further be categorized into two groups: the integrated collector storage systems and the thermosyphon SWH systems.

In the integrated collector-storage systems (also called batch systems), the storage tank acts both as a storage apparatus and as a solar collector apparatus. Heat loss, which is more intense in the night, is one of the major drawbacks of this class of passive systems. Figure 5.4 shows the structure of an integrated solar collector/storage system. The geometrical shape of the combined collector/storage apparatus (cylindrical, triangular, and pyramidal shapes) can determine the heat production efficiency and the insulation material type (fibre glass, inorganic glass forms, and organic-based foams) can influence the thermal performance of the system (Burns, Zeenni & Guven, 1985; Goetzberger & Rommel, 1987; Shukla *et al.*, 2013).

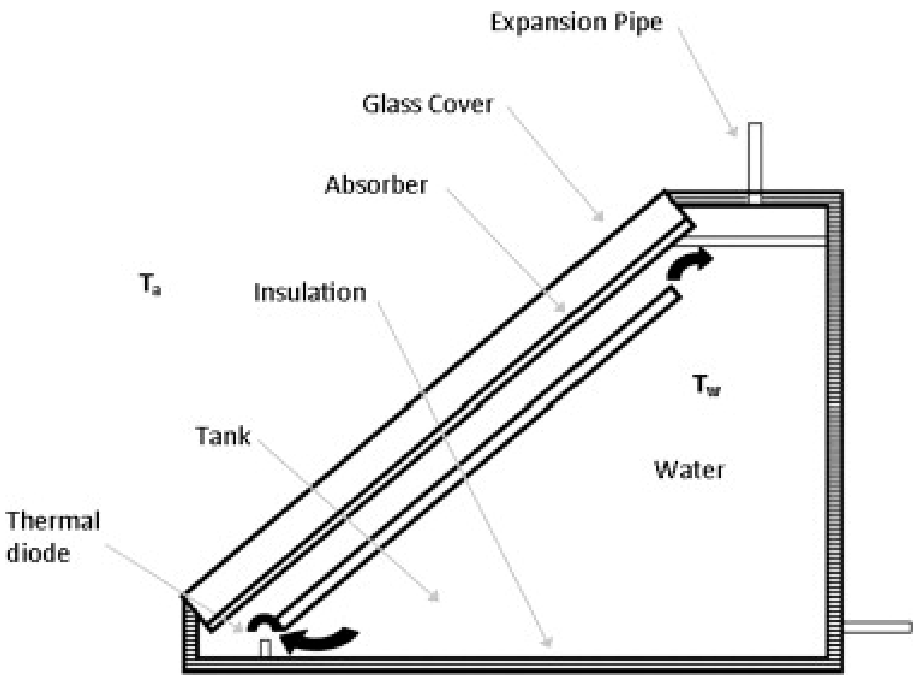


Figure 5.4: A schematic of an integrated collector-storage solar tank (Shukla *et al.*, 2013)

Thermosyphon SWH systems are passive systems that do not use a pump and the collector and the storage tanks are distinct (un-integrated) units. Figure 5.5 shows the structure of an integrated solar collector/storage system. In the late 19th century, thermosyphon SWH replaced integrated collector systems due to the excessive loss associated with the latter (Shukla *et al.*, 2013).

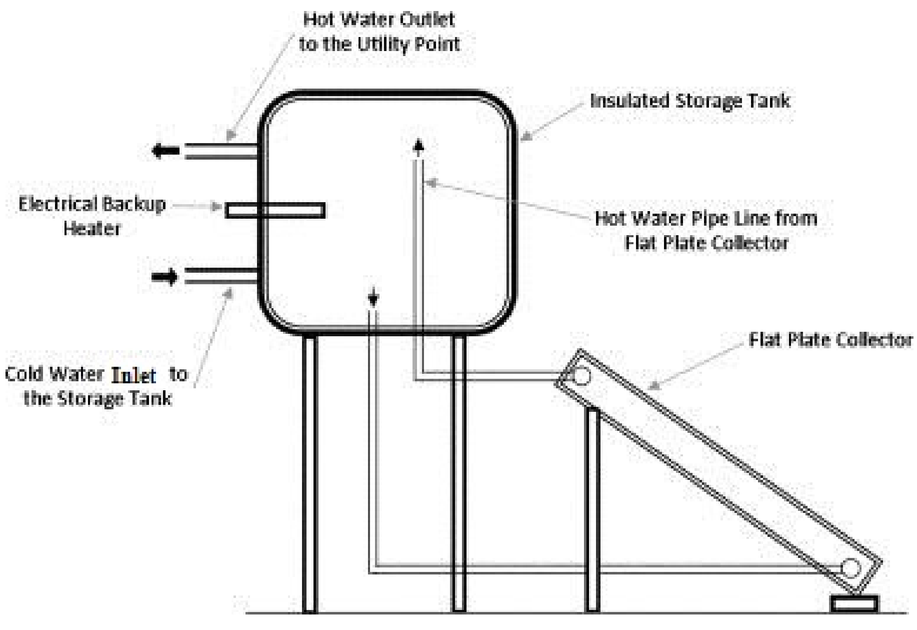


Figure 5.5: A schematic of thermosyphon SWH system (Shukla *et al.*, 2013)

Active Systems: Active systems are SWH systems equipped with one or more pumps to circulate the working fluid of the SWH system. In addition, active systems are classified into two groups: direct (or open loop) systems and indirect active systems.

The indirect active system achieves the circulation of heat transfer fluid, such as ethylene glycol and other refrigerants, through the collector and rejects heat through the heat exchanger in the storage tank.

In the direct active system, water to be heated in the storage tank is circulated through the collector (Shukla *et al.*, 2013). Direct active systems could supply hot water of moderate temperature (50 to 60°C) but their performance is sensitive to freezing conditions (Kalogirou, 2004b) although some design modifications, such as operating the system in a so-called ‘drain-back’ mode, exist that overcome the freezing related issues (Shukla *et al.*, 2013). Examples of direct mode of SWH systems include the flat-plate collectors, the evacuated (vacuum) tube collectors (Li *et al.*, 2010), and the V-trough SWH systems (Chong, Chay & Chin, 2012).

Generally, direct SWH systems are popular in regions that experience moderate ambient temperature and with a lot of sunshine. Indirect SWH systems, which are reliable and effective in relation to freezing protection, are popular in regions with less sunshine and low ambient temperature (Kalogirou, 2004b). Given the high ambient temperature in KSA particularly in the summer, the direct SWH systems are the most suitable in this region of the world.

5.3 Review of Previous Studies

Amongst solar water heating collectors (flat plate, evacuated tube and other type of collectors), the flat plate are by far the most common in the residential application sector due to their lower cost and ease of use (Leidl & Lubitz, 2009). A good flat plate collector can absorb up to 96% of the incident solar energy (Lunde, 1980).

Pumps, although not compulsory, are useful since storage tanks, which are susceptible to freezing conditions, must be placed above the collector (Ramlow & Nusz, 2006). Importantly, in a country like Canada where the potential for freezing and deposition of minerals in the heat exchanger is high, closed loop SWH systems are by far the most installed (Leidl & Lubitz, 2009). On the world-wide scale, the distribution of SWH system types (passive and pumped types) as of 2015 is shown Figure 5.6 (Weiss, Spörk-Dür & Mauthner, 2017). A comparison of the flat-plate collector and the evacuated-tube collector are given in Table 5.1. For the case of China, some performance of evacuated tube and flat plate collectors are given in

Table 5.2 (Qiu, Ruth & Ghosh, 2015).

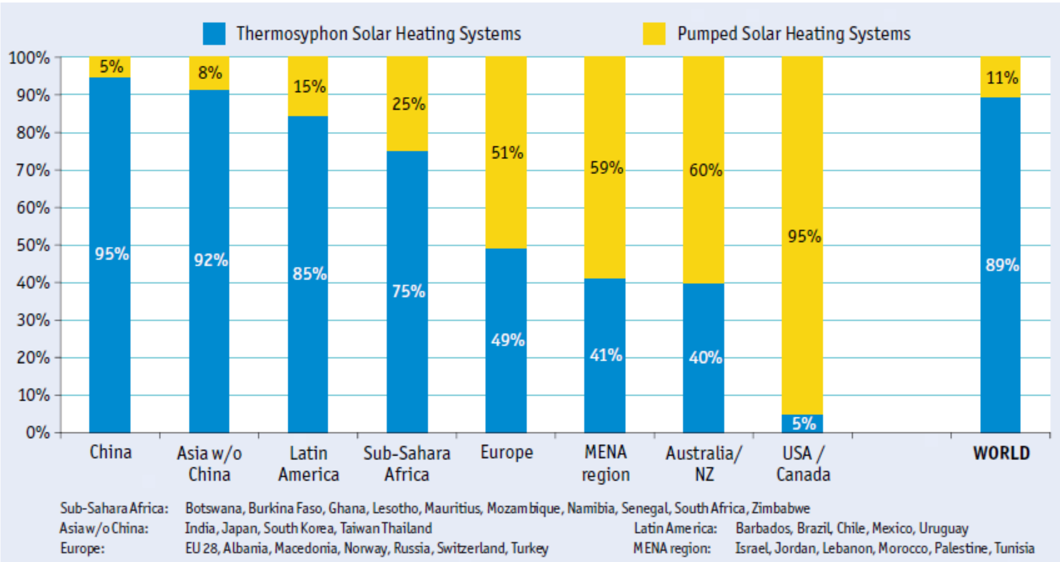


Figure 5.6: The distribution of SWH system types (passive and pumped types) as of 2015 (Weiss, Spörk-Dür & Mauthner, 2017)

Table 5.1: A comparison of the flat-plate collector and the evacuated-tube collector (Wang *et al.*, 2015)

	Flat-plate collector	Evacuated-tube collector
Heat production	Slow	Rapid – vacuum prevents heat losses
Heat losses during daytime	High	Negligible
Influence of the incidence angle of the sun rays	Maximum solar absorption at noon – flat shape	Maximum solar absorption throughout the day – cylindrical shape
Cold weather operation	Limiting effect – direct heat transfer processes, risk of freezing	Satisfactory performance – vaporising/condensing processes within the heat pipes
Maximum operating temperature range	Up to 80°C	Above 120°C
Cost-effective	Old technology at higher price	Advanced technology at competitive price
Hot water availability	For 300 days throughout the year	For 350 of days throughout the year – high efficiency
Position of the collector on the roof	Preassembled flush with the roof – lifting may be required	Assembled onto the surface of the roof

Table 5.2: Performance of evacuated tube and flat plate collectors in China (Qiu, Ruth & Ghosh, 2015)

Indicator	Flat-plate collector	Evacuated-tube collector
Daily average efficiency	48–58%	45–50%
Heat loss coefficient	Greater than 1.2 W/(m^2 °C)	Less than 1.2 W/(m^2 ˚C)
Instantaneous efficiency	Best for less than 32°C above ambient	Best for more than 32°C above ambient
Anti-freezing	Poor	Good
Tolerance of pressure	High	Low
Integration with buildings	Easy	Difficult
Life cycle	20–30 years	10–15 years

For SWH systems, two payback periods are often defined: the "simple energy payback" period is the length of time that the annual savings of a SWH system accumulates to the initial cost of investment (Mccarter & Mccarter, 2011), and the "displaced energy payback" period is the ratio of the embodied energy cost to the annual energy savings, where the embodied energy cost is the cost of the total energy required to manufacture the SWH system (that includes, the direct and indirect costs such as the cost of the raw materials, and maintenance of the SWH system over its useful lifetime) (Hernandez & Kenny, 2012a) .

In the analysis given in (Allen *et al.*, 2010), the simple payback period for a SWH system in the UK is between 2.9 – 5.2 years, and the displaced payback period for a SWH system is approximately 2.4 years when installed alongside a gas boiler, approximately 1.9 years with an oil boiler, and approximately 1.3 years with an electrical immersion heater. The electrical immersion heater provides the shortest displaced payback period because it entails the greatest overall energy resource saving per unit of solar-derived hot water (in fact, it has been reported that the displaced payback period for a SWH system with an electrical immersion heater could be as low as 0.7 years). All these energy payback are based on the analysis of a 2.8 m^2, freeze-tolerant, flat-plate collector SWH system whose inlet water is provided by means of a solar photovoltaic-powered pump with varying flow-rate depending on the available solar insolation. These payback periods are short compared to the estimated lifetime of SWH systems which is around 25 years. In a study conducted in (Hernandez & Kenny, 2012b), the displaced energy payback period is between 1.2 and 3.5 years in Ireland.

A summary of displaced payback periods for SWH systems from previous studies is given in Table 5.3. It should be pointed out that the displaced energy payback calculations in all the studies on the table have all been performed in countries with favourable climatic conditions (high solar irradiation, in particular) for SWH systems and are based on estimated predictions (and not on the real measurement) of the performance of the installed SWH system.

Table 5.3: The displaced payback period of SWH from previous studies

Author	Solar collection area (m^2)	Location	Displaced Energy Payback Period
(Mathur & Bansal, 1999)	2	Various locations, India	0.7 – 4.1
(Crawford & Treloar, 2004)	3.8	Melbourne, Australia	0.2 - 2
(Ardente *et al.*, 2005)	2.13	Palermo, Italy	< 2
(Kalogirou, 2004a)	3.8	Nicosia, Cyprus	1.2
(Battisti & Corrado, 2005)	1.7	Rome, Italy	0.4 – 1.6

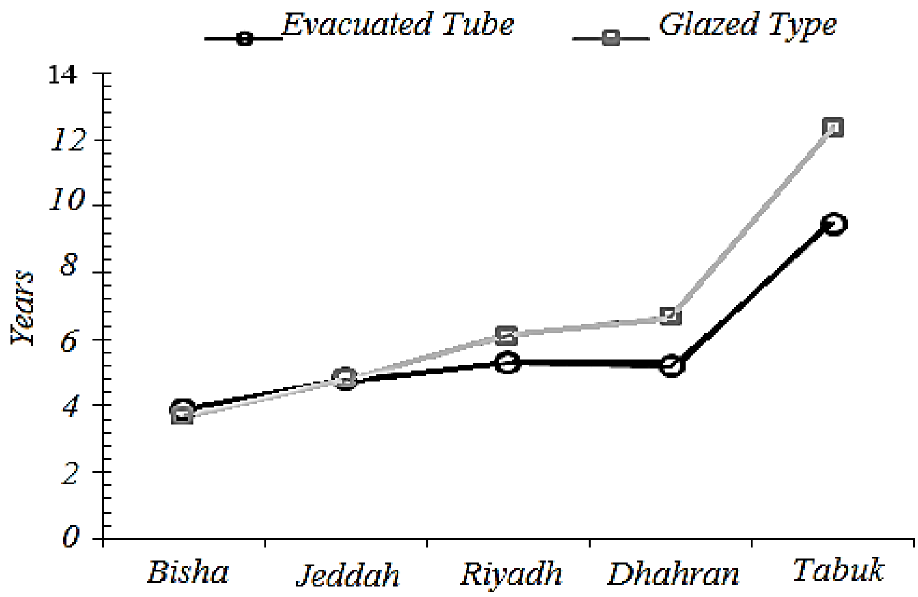
Some of the technical problems that are barriers to the wide spread adoption of SWH are high heat loss (particularly at night), high capital cost and challenges related to their installations in buildings (such as lack of space) and those which may also affect building's aesthetic view (Wang *et al.*, 2015).

Comprehensive literature review on the operation, performance improvement strategies, modification schemes, and limitations of existing technologies of SWH systems can be found in (Jaisankar *et al.*, 2011). Generally, improvement that can be made in the design of the collectors in order to increase their efficiency is an area of on-going research and development (Shukla *et al.*, 2013).

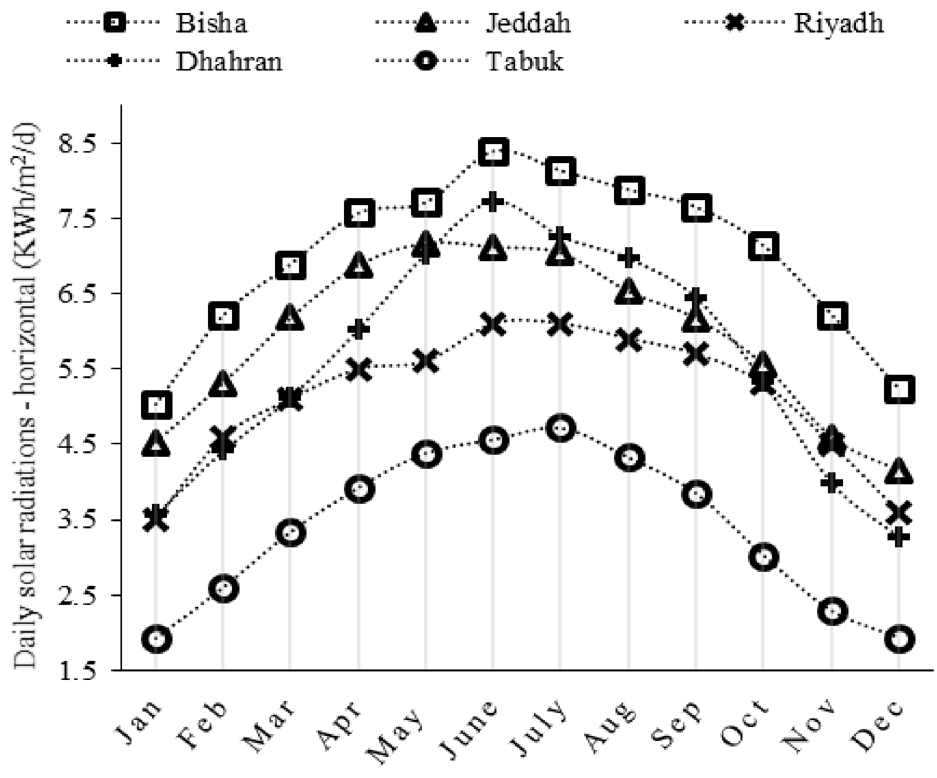
In the past, most countries of the Gulf Cooperation Council (GCC) do not have policies that seriously encourages the usage of solar thermal systems – largely due to the greatly subsidized price of electricity and the abundance supply of energy from fossil fuels (Al-Badi, Malik & Gastli, 2009; Abd-ur-Rehman & Al-Sulaiman, 2016); however, with the current price of crude oil and the depletion of fossil fuels, these countries are beginning to look into renewable energy systems as a viable alternative for meeting their increasing energy needs.

Despite the recognition of SWH systems as a renewable energy source, their potential to provide energy during peak time in the case of KSA has not been fully appraised. Generally, the efficiency of solar energy systems peaks in the summer during which the energy demand of KSA is greatest, the deployment of WHS systems can therefore reduce peak energy demand.

(Abd-ur-Rehman & Al-Sulaiman, 2014) assessed the techno-economic viability of SWH technologies for domestic use in KSA. It evaluated two different collector types (evacuated tube and glazed type collectors) for SWH applications using the RETScreen software – a software widely used for calculating life cycle assessment and energy production of SWH systems – and reported numerical results for five cities (namely, Jeddah, Dhahran, Tabuk, Riyadh and Bisha) spread across KSA's geographical regions. Based on the analysis of solar radiation on horizontal and tilted surfaces, solar fraction, benefit to cost ratio, annual life cycle savings, and fuel savings, it concluded that while Tabuk is the least suitable place for SWH technology (mainly because of high initial cost and long simple energy payback period), because it has less solar radiation intensity and needs at least three flat-plate or two evacuated -tubes collectors to meet the requirement. Bisha is the most attractive for the technology (refer to Figure 5.7 (a)). Moreover, Jeddah, Dhahran and Riyadh also demonstrate pronounced financial advantage. Figure 5.7 (b) shows the solar radiation (horizontal) for these five cities for a typical day – it is clear that solar radiation play a very significant role for SWH performance.



(a)



(b)

Figure 5.7: (a) Simple payback period, and (b) monthly variation of daily solar radiation for 5 cities in KSA (Abd-ur-Rehman & Al-Sulaiman, 2014)

For arriving at the simulation results in (Abd-ur-Rehman & Al-Sulaiman, 2014), hot water use for households in the US was assumed for KSA which is a drawback given the difference in culture, policy, energy cost, and the level of awareness on the need and importance for energy consumption and conservation in the two countries. In particular, the assumptions made in (Abd-ur-Rehman & Al-Sulaiman, 2014) are presented Table 5.4

Table 5.4: Modelling assumptions for the techno-economic analysis of SWH technologies for domestic use in KSA given in (Abd-ur-Rehman & Al-Sulaiman, 2014)

Factor	Value
No of occupants	6
Occupancy rate	80%
Daily hot water use per person	48 l/day
Hot water temperature	60°C
Operating days per week	7
Collector slope	Latitude of location
Miscellaneous losses of collectors	5%
Storage Capacity per Solar Collector Area	75 l/sq. m
Heat Exchanger availability	NO
Fuel type (backup fuel)	Electricity
SWH system seasonal efficiency	90%
Fuel rate	0.030 $/KWh
Initial contingencies (labour, transportation etc.)	5%
Annual cost (operation & maintenance)	5%
Fuel cost escalation rate	4%
Inflation rate	2.5%
Project life	15 years
GHG emission factor	0.755
GHG credits transection fee	1%
GHG reduction credit rate	15$/tCO2
GHG reduction credit duration	7 years

The residential sector in Oman – a country which is very similar to KSA in terms of climate, culture, energy policy and energy cost – is the largest consumer category for electricity consumption taking more than 50% of the total electrical energy produced in the country (Al-Badi *et al.*, 2009).

A study on the financial, economic and technical analysis of using SWH systems in residential units of Oman – a country of 2.8 million people with 551,058 housing units as of 2010 – is presented in (Al-Badi & Albadi, 2012); using SWH systems in all its governorates, the potential energy savings per day of 5,093.20 MWh and per year of 1,859 GWh is estimated. This estimate however assumes that all housing units have only 3 electric water heating units and disregards variation in the number of members in households – which are very important factors for accurate predictions. The model used for prediction, for simplicity, also assumes that the electric water heaters are used only for 150 days in a year and for 5 hours on each of these days although it is likely, in this author's observation, that electric water heaters are used throughout the year in many bathrooms and kitchens. The simple energy payback period for a SWH system in Oman is estimated to be 6 years. The energy savings possible through the adoption of SWH systems for KSA will be compared further with that of Oman later in this chapter.

5.4 Methodology

The main goal of this chapter is to find the reduction in peak electricity demand achievable when domestic hot water is supplied using SWH systems in KSA. Climatic factors, human behaviour, house types and family size are factors influencing the volume of hot water consumption and, consequently, the energy consumption due to hot water production in a given household. The study here will provide new perception on the deployment of SWH in KSA and a case study of Riyadh city in KSA is presented – in order to determine the electricity demand reduction that can be achieved from a large scale deployment of SWH in the city. In order to achieve our goal of estimating the energy production that can be obtained through SWH adoption, the following steps are followed:

- Obtain a model to determine the hot water requirement for households for different number of members in KSA. The majority of the households in KSA (for instance, more than 71% for the city of Riyadh as will be seen later) have between 2 to 5 bedrooms. For Riyadh, the number of individuals in these categories of house types is about 4,120,819 – which is approximately 80% of the number of individuals in that city. Starting with the prediction of hot water requirements of house types of 2 to 5 bedrooms, the model that is obtained at this stage will be used to predict the hot water consumption for each house type and the sum of these will be the hot water requirement for the population.
- For each category of house type, determine the energy requirements for a given amount of hot water consumption per day. While the previous step gives the amount of hot water requirement per day, the present step computes the energy required for the production of the required amount of hot water per day. This is achieved using the estimates of the inlet (cold water) and outlet (hot water)

temperatures of the water as well as the estimate of the hot water consumption profile for a typical day. The estimated values for each day in this step are compared with actual values that were taken from actual measurements of few households in Riyadh taken daily to provide the confidence that the model truly represents the energy consumption in the real world including the associated losses. Thereafter, the average electrical energy that can be saved through the adoption of SWH system by each household of different number of occupants is estimated.

- ❖ Using national population data of KSA for the city of Riyadh as well as monthly ambient temperature for the whole year, determine for each category of households (i.e. categorized based on the number of bedrooms: 1, 2, 3, 4, 5, 6 and 7+):
  - the distribution of hot water use over the day
  - the amount of useful energy delivered on deployment of SWH systems
- ❖ For a given percentage of the total number of households in the city of Riyadh, determine:
  - the distribution of hot water use over the day
  - the amount of electrical energy to be saved on deployment of SWH systems

  In other words, while the previous step deals with each individual category, this step deals with fractions (percentage) of the population for each category.
- ❖ Calculate the reduction in peak electricity demand if a given percentage of Riyadh city's population (obtained in the previous step) deploys SWH systems.

5.5 Solar Water Heating System in KSA

From the model given in (EST, 2008) based on measurements in approximately 120 UK households, the average hot water requirement per day for a household of ***N*** members can be computed using the following formula:

$$\boldsymbol{Hot\ water/day\ = 46 + 26 \times N} \qquad \textbf{(5.1)}$$

(Including the modelling standard errors, the slope is 26$\pm$7 and the intercept 46$\pm$22).

A discussion will follow later in this section on the reasonability and justification of using this model for households in KSA. For now, consider the case of a household of five members in the city of Riyadh, that is $\boldsymbol{N = 5}$, then using this model (equation 5.1), the daily hot water consumption per day is given as:

- The hot water consumption of a household of five members in the city of Riyadh = 46 + (26 × 5) = 176 litre/day.

The equation computing the hot water energy requirement per day as follows:

$$\boldsymbol{Hot\ water\ energy/\ day = Hot\ water\ volume/day\ \times\ C \times T} \qquad \textbf{(5.2)}$$

where C is a constant (the specific heat capacity of water) and is equal to 1.16 Wh/kgK and T is the temperature difference between the cold water (inlet) and the hot water (outlet).

Consequently, for the household under consideration, the hot water energy requirement per day is as follows:

- Hot water energy requirement per day = 176 × 1.16 × (60 – 31) = 5.92 kWh/day

where 60^{o}C is the outgoing (outlet) hot water from the water heaters (for hygienic use, water heaters are commonly set to this temperature as this is temperature needed to ensure Legionella bacterium is killed), and 31^{o}C is the temperature of the in-going (inlet) water. Obviously, the 60^{o}C figure only relates to the hot water at the source (the point of production); for practical use in households (for bathing, washing, and so on), this water is suitably diluted by users.

Here, a household of five and the temperature of the water going into the water heaters is about 31^{o}C on a yearly average is considered. It is very difficult to come by the actual temperature of cold (tap) water in KSA. In the absence of data relating to the temperature variation of tap water in KSA over the year, it will be assumed that the temperature of the tap water is equivalent to the temperature of soil that is approximately 0.75 m and 1.35 m below the ground were water pipes are usually laid. It has been indicated that the monthly normal maximum soil temperature at 1 metre below the ground for the city of Riyadh is 31^{o}C (Dafalla, 2008) and this value has been used for the calculation here.

In order to justify applying the model developed for the UK as a model for KSA, we will consider the case of two households in the city of Riyadh in the next section.

5.6 A Case-study of Riyadh

The majority of the homes in KSA do not have a central water heating system. In fact, in almost all cases, the installation of the electric water heating system is at each point of use and therefore, there are several water heaters in each home. A typical installation of a water heating system in a bathroom of a home in KSA is shown in Figure 5.8.

Figure 5.8: Picture of a typical water heater system installation (Author)

In this study, measurements of the electricity consumption of three water heaters in two different homes that are typical of homes in KSA were taken daily for 7 to 12 consecutive days from the electricity meters at 11:00 pm daily by the home occupants.

Table 5.5 shows the measured electricity consumption of a hot water heater of 100 litres capacity installed in the kitchen of a household with five members in the city of Riyadh.

Table 5.6 explores the measured electricity consumption of the hot water heater of 50 litres capacity installed in one of the bathrooms for the same household. The daily averages of the electric power usage for the kitchen and the bathroom, as given on the tables, are 3.255 kWh and 1.0027 kWh, respectively. The household has one kitchen and three bathrooms (one for each of the three bedrooms). Assuming that the average usage of hot water is the same for all the three bathrooms, the total hot water energy consumption per day for this household is:

- The hot water energy/day = 3.255 + 3× 1.0027 = 6.26 kWh.
- This value is close to that arrived at earlier for a household of 5 members through use of the UK model (i.e. 5.92 kWh).

For another household of six members in Riyadh, the measured electricity consumption of a hot water heater of 100 litres capacity installed in the kitchen is given in

Table 5.7 where the daily average of the electric energy usage is 5.12 kWh. This household also has three bathrooms, and assuming that the average usage of hot water in the bathrooms is the same as in the previous household of 5 members, the total hot water energy consumption per day for this household is:

- The hot water energy/day = 5.12 + 3× 1.0027 = 8.12 kWh.

Using the UK model (equation 5.1) for this household the hot water consumption for this household would be:

- The hot water energy/day = 6.80 kWh (i.e. [46 + (26 × 6)] × 1.16 × (60 – 31)).

It is important to note that the calculated (average) value using the UK model is slightly lower than the actual values of the two households considered. However, the calculated values have not taken into account the cooling losses. These losses must be added to the energy output of the SWH system in order to estimate the total energy output that the SWH will have to produce. Although the readings of two households are used in this analysis, given that the population of Riyadh is approximately 6,506,700 with 1,116,339 households and an average of 5.7 persons per household as at 2016 (HCDR, 2016), in the absence of any statistics (as far as this author is aware) that provides concrete information on the domestic usage of hot water in KSA (or, Riyadh city) at household level, given the consistency between the UK model and the measured data, it is reasonable and justifiable to make further use of the UK model in this analysis.

In addition, the cooling loss per day can be taken as 0.59 kWh from the first day of Table 5.6 since it is known that hot water was not used on that day.

Table 5.5: The electricity consumption reading of hot water heater of 100 litres capacity installed in the kitchen of a household with five members in the city of Riyadh

Day No.	Reading kWh	Daily Consumption kWh
1	2.42	-
2	3.79	1.37
3	8.31	4.52
4	11.81	3.5
5	15.59	3.78
6	19.28	3.69
7	21.95	2.67
	Average of 6 Days	3.26

Table 5.6: The electricity consumption reading of hot water heater of 50 litres capacity installed in a room of a household with five members in the city of Riyadh

Day no.	Reading kWh	Daily Consumption kWh
1	2.85	-
2	3.44	0.59
3	4.48	1.04
4	5.76	1.28
5	6.98	1.22
6	7.85	0.87
7	8.71	0.86
8	10.15	1.44
9	11.28	1.13
10	12.16	0.88
11	13.13	0.97
12	13.88	0.75
	Average of 11 Days	1.0027

Table 5.7: The electricity consumption reading of hot water heater of 100 litres capacity installed in the kitchen of a household with six members in the city of Riyadh

Day No.	Reading kWh	Daily Consumption
1	2.89	-
2	8.28	5.39
3	13.52	5.24
4	18.75	5.23
5	23.52	4.77
6	28.74	5.22
7	33.59	4.85
	Average of 6 Days	5.12

To determine the impact of SWH on peak electricity demand, data on the distribution of hot water use over the day is needed. The average distribution of hot water use over the day (measured by the energy requirement) for the UK as given in (EST, 2008) is shown in Figure 5.9. In the author's judgement and experience, the morning and evening peaks in usage shown in Figure 5.9 also occur in KSA. From this plot, the total average daily consumption obtained by adding all the bars is 4.69 kWh. In UK, the working day mostly starts at 9:00 am, but in KSA, the working day mostly starts at 8:00 am. To align this cultural difference in daily routine, shifting the plot of Figure 5.9 by one hour forward, and then scaling all the bars up by multiplication with a constant value (5.92/4.69=1.26) so that the sum of the bars equates to 5.92 kWh gives Figure 5.10 which represents the energy use in a 5 person household.

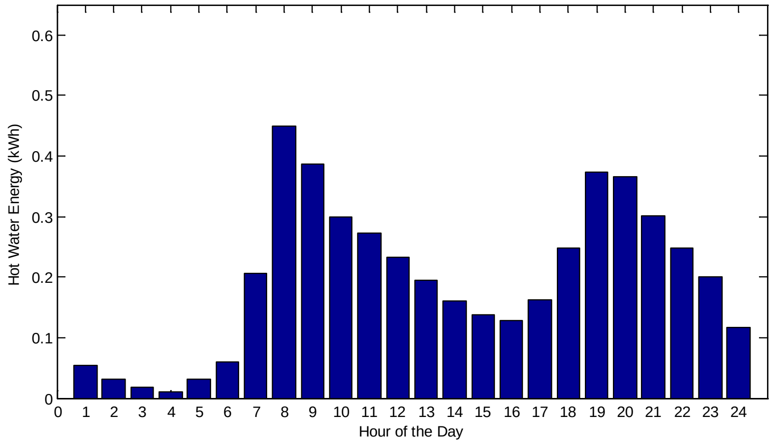


Figure 5.9: Average energy consumption of hot water heaters in the UK

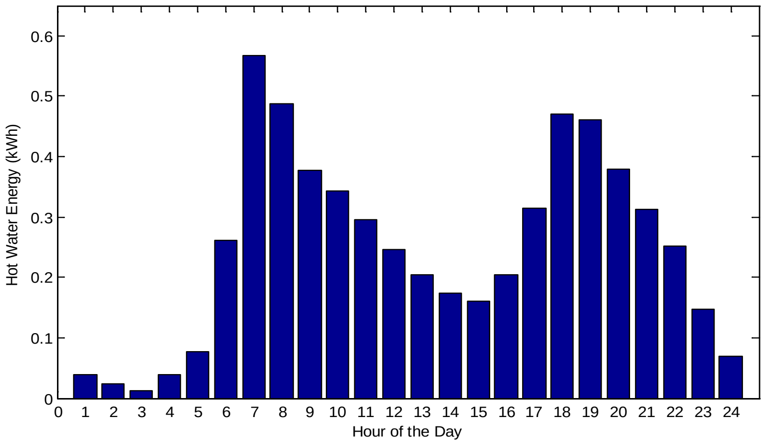


Figure 5.10: Average energy consumption of hot water heaters in KSA of a household of five members with 5.92 kWh consumption of hot water per day

- The consumption of household of N = 4: [46 + (26 × N)] × 1.16 × (60 – 31) = 5.05 KWh
- The consumption of household of N = 3: [46 + (26 × N)] × 1.16 × (60 – 31) = 4.17 KWh
- The consumption of household of N = 2: [46 + (26 × N)] × 1.16 × (60 – 31) = 3.30 KWh

The equivalent plots of the households of four, three and two obtained by appropriate scaling of Figure 5.10 are given in Figure 5.11, Figure 5.12 and Figure 5.13, respectively.

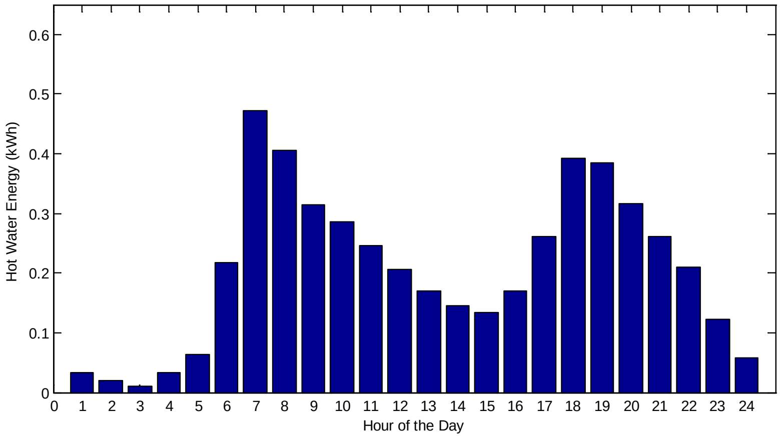


Figure 5.11: Average energy consumption of hot water heaters in KSA of a household of four members with 5.05 kWh consumption of hot water per day

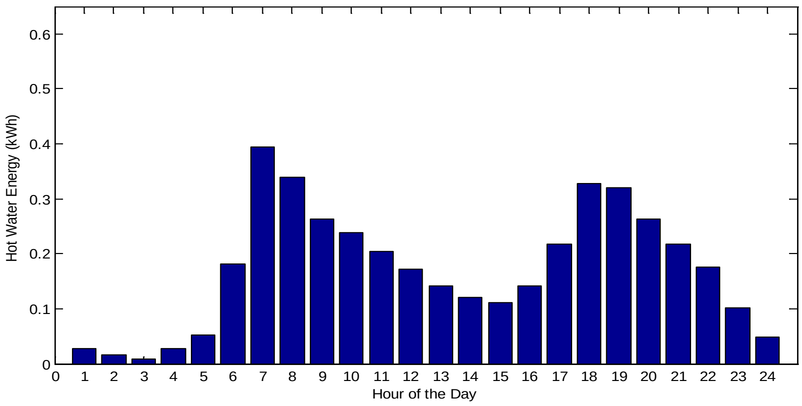


Figure 5.12: Average energy consumption of hot water heaters in KSA of a household of three members with 4.171 kWh consumption of hot water per day

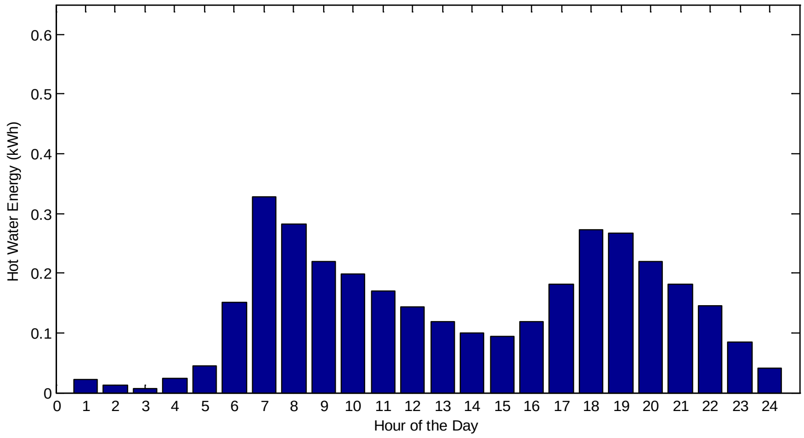


Figure 5.13: Average energy consumption of hot water heaters in KSA of a household of two members with 3.297 kWh consumption of hot water per day

Now, if all hot water needs are to be met by solar thermal energy, then for each of the households with members of 2, 3, 4 and 5, the average energy requirements of hot water heaters (i.e. the average energy that will be saved by using solar thermal heaters instead of electricity from the grid) can be obtained by summing the hourly hot water requirements given in Figure 5.11 – 5.13; that gives the following (assuming the daily fixed loss per heater is 0.59 kWh and, according to the survey, the majority of the households have 3 heaters). The average energy saved by the household of 2 is 5.07 kWh (3.297 kWh + 3× 0.59 kWh = 5.067 kWh), and by similar computation, the average energy requirement of households of one to seven members including fixed losses are given in Table 5.8.

Table 5.8: A summary of average energy requirement of households

Household No.	The average energy in kWh
1	4.19
2	5.07
3	5.94
4	6.82
5	7.69
6	8.57
7	9.44

According to KSA's General Authority of Statistics (GAS, 2016; HCDR, 2016) for a total number of households of 809,437 in the city of Riyadh surveyed from the total of 1,116,339 households, the number of households and the number of individuals that falls in the categories of households are given in Table 5.9.

Table 5.9: Number of households surveyed in the city of Riyadh

No. of Bedrooms	No. of Households	No. of Individuals in this Category	Percentage of Total No. of Households (%)
1	54683	177627	6.8 %
2	223642	1067961	27.7 %
3	210327	1314486	26.0 %
4	144466	1029284	18.0 %
5	89062	709088	11.0 %
6	49951	437913	6.2 %
7+	37306	389745	4.6%
TOTAL	809437	5126104	100%

Assuming that 30% of the 1,116,339 households in Riyadh are to move to solar thermal, the numbers of households corresponding to this value are given in Table 5.10. An estimate of 30% has been assumed to be practical and realistic to explore the scenario that the government of KSA are able to enact a policy to encourage mass deployment of SWH systems in residential buildings. The total contribution of each of the household categories on Table 5.10 is computed by summing up, for each category, the contribution of all the households for energy requirement (including fixed losses) in that category. The daily total electrical energy savings accomplished as shown on the table is 2,094.2 MWh.

Table 5.10: Number of households to deploy solar thermal in the city of Riyadh

No. of Bedrooms	Percentage of Total No. of Households (%)	30% of Households (334900)	Daily Total Contribution of Category (MWh/day)
1	6.8 %	22625	94.9
2	27.6 %	92531	468.9
3	26.0%	87022	517.0
4	17.9 %	59772	407.4
5	11.0 %	36849	283.4
6	6.2 %	20667	177.0
7+	4.6 %	15435	145.7
TOTAL	100 %	334900	2094.2

Figure 5.14 shows the distribution of electrical energy saved by 30% of households (334900 households) in Riyadh deploying solar thermal on a given day. Thus, if 30% of households (334900 households) in Riyadh are moved to solar thermal, the daily saving in energy is about 2,094 MWh.

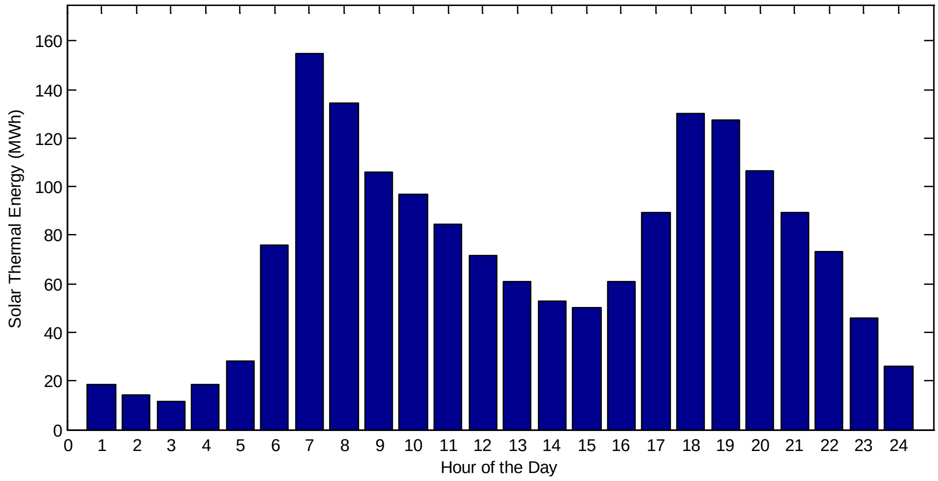


Figure 5.14: Distribution of energy delivered by 30% of households in Riyadh deploying solar thermal on a given day.

For comparison with the energy harvested from solar PV systems of chapter 3, the electrical energy saving during the peak time – from 10:00 am to 17:00 pm for a typical day – is 688 MWh from the plot of Figure 5.14. The average reduction in electricity demand due to this saving is about 98 MW (that is, 688 MWh/7hrs). This value is small compared with 2,392 MW if solar PV system were deployed during peak time as computed in Chapter 3.

5.7 Discussion

In the previous section, the energy savings that can be accomplished if around 30% of households in Riyadh city are to move to SWH systems for the provision of their domestic hot water requirements. The summary of the results are as follows:

- 30% of Riyadh households of 1,116,339 as of 2016: 334,900 residential units
- 30% of Riyadh's population of 6,506,700 as of 2016: 1,952,010 people
- Per Day (24 hours) – i.e. Total energy savings per day: 2,094.2 MWh
- During Peak Time (7 hours) – i.e. Energy saving during daily peak period: 688.35 MWh.
- During the peak hour (14:00 to 15:00 – the peak time is 14:22 from the chapter 1), the energy saving is 51.5 MW.

In order to ascertain that these results are reasonable, it would be useful to compare the results with a previous study in a country similar to KSA (as no previous study of this has been carried out for KSA as far as this author is aware of). The results of a study on the financial, economic and technical analysis of using SWH systems in residential units of Oman as presented in (Al-Badi & Albadi, 2012) are summarized as follows:

- Number of households in Oman as of 2010: 551,058 residential units
- Oman's population as of 2010: 2,800,000 people
- Total energy savings per day (Annual savings/365: 1859GWh/365): 5,093.20 MWh

For comparison, the results, the model parameters and assumptions for Riyadh city and Oman are summarized in Table 5.11.

Table 5.11: Comparison of models for obtaining total energy savings

Riyadh City	Oman (Al-Badi & Albadi, 2012)
30% of Riyadh households of 1,116,339 as of 2016: 334,900 residential units	Number of households in Oman as of 2010: 551,058 residential units
30% of Riyadh's population of 6,506,700 as of 2016: 1,952,010 people	Oman's population as of 2010: 2,800,000 people
Per Day (24 hours) – i.e. Total energy savings per day: 2,094.2 MWh, [During Peak Time (7 hours) – i.e. Energy savings during daily peak period: 688.35 MWh]	Total energy savings per day (Annual savings/365: 1859GWh/365): 5,093.20 MWh
Model considers housing units of 1 to more than 7 bedrooms and various number of house members; therefore, varying number of hot water requirements but with fixed (i.e. three) electric water heating system units.	Model assumes that all housing units have only 3 electric water heating units and disregards variation in the number of members in households.
Model considered variation in hot water heating requirements for each hour of the day.	Model assumes that electric water heating units (each rated at 1500W) are used on full capacity only for 5 hours in a day.
Model considered the use of electric water heaters throughout the year.	Model considered that electric water heaters are used only for 150 days (and for 5 hours on each of these days) in a year.

From Table 5.11, it is clear that the total savings computed for Oman is significantly higher (about twice what would be expected) than that of Riyadh city. The total energy savings per day per person is approximately 1.07 KWh and 1.82 KWh for KSA and Oman, respectively. However, given that the results of Oman ignored an important parameter, which is the number of members per household as well as fixed the hot water requirements for all household in Oman, the computed values for Riyadh in this study appear to be more realistic.

In KSA, electricity-powered water heating systems are the most common. Therefore, the adoption of SWH may offer significant cost savings for households. The results in this chapter has shown that the use of SWH systems should be heavily promoted in both existing homes and new home developments in order to reduce demand on the national grid during peak hours.

5.8 Limitations of this Study

A model of hot water consumption derived from a UK survey has been used, with the justification that it gives values consistent with measured consumption in typical homes in Riyadh. The amount and distribution of domestic hot water use in Riyadh may, however, vary slightly from the assumptions employed here given the difference in culture, energy policy and energy cost of the two countries. Future research work in this area should focus on finding models that are based on statistical data obtained from KSA's households.

5.9 Summary

In this chapter, the reduction in peak electricity demand achievable when domestic hot water is supplied using SWH systems in KSA was presented. As a case study, the electricity demand reduction that can be achieved from a large scale deployment of SWH in the city of Riyadh was considered. Starting with the prediction of hot water requirements of house types, and computing the energy required for the production of the required amount of hot water per day using the estimates of the inlet (cold water) and outlet (hot water) water temperatures and the hot water consumption profile for a typical day, the average electrical energy that can be saved through the adoption of SWH system by each household of different number of occupants was estimated. As a case study, the results of Riyadh city were presented. In summary, if 30% of households (334900 households of a total of 809437) in Riyadh are moved to solar thermal, the daily saving in electricity is about 1,677 MWh. The reduction in average electricity demand due to this saving is about 69.88 MW (1,677.3 MWh/24hrs). In particular, during the peak hour (14:00 to 15:00), the power saving is 51.5 MW. These results were compared with a previous study for Oman – a country similar to KSA in climate, culture and energy usage. The computed values for Riyadh presented in this study appear to be realistic.

Chapter 6: Discussion

6.1 Introduction

Electricity consumption in KSA has grown by about 7% annually in the last two decades as a result of population and economic growth. The consumption of the residential sector accounts for over 50% of the total energy generation. In the summer, the consumption of residential buildings' air conditioning reaches up to 60% to 70% of the total electricity consumption of these buildings (ECRA, 2014; Alrashed & Asif, 2014). This factor contributes significantly to a situation where peak electricity demand occurs early afternoon and lasts for about five hours during the summer months. In order to tackle this challenge, this research focused on the most applicable and promising solutions to manage the electricity peak demand of the residential sector of KSA that will conform to national strategies and policies. It does so by taking advantage of renewable energy technologies and smart grid management options. To achieve that, as presented in the preceding three chapters, the research proposed and investigated the following solutions:

1. The deployment of PV panels with a slope and orientation that optimises their output with respect to the timing and shape of the demand profile taking into account the reduction in the performance of solar PV systems due to the accumulation of dust.
2. The deployment of operational strategies for AC by appropriate smart scheduling and control or by the service of the utilities to remotely set the thermostats of the AC without compromising indoor air quality and comfort of occupants.
3. The deployment of solar thermal systems as a source of domestic hot water to reduce the use of electric water heating systems.

The deployment of the PV systems and the solar thermal water heating systems are to supply energy while the smart scheduling and control or remote control of AC system are to manage the energy consumption on the distribution network. In relation to the supply electricity, since electricity companies are generally government-owned, existing roofs of government buildings (particularly, schools, malls and mosques) in residential neighbourhoods were exploited in order to install solar panels – thereby assisting the supply side during peak times. For the same purpose, thermal solar panels were adopted for residential water heating. In relation to the demand side, smart solutions were proposed in the form of DSM through the use of intelligent (or smart) control of thermostat settings via scheduling and advance control of the operation of AC systems and in the form of the DR through remotely setting the thermostats of the AC for air conditioning systems' operations. It was essential that the study of the occupancy behaviour was carried out through a survey in order to successfully analyse the DR and DSM techniques that were proposed. Analyses of all the proposed solutions were carried out by estimating the potential savings in peak electricity demand that has to be supplied by large scale conventional power plants.

In this chapter, further discussion on these solutions including their effectiveness, their large-scale deployment and their possible combination is presented. The findings are broadly applicable to other countries, particularly those in the Middle East, with similar climatic conditions and electricity usage behaviour and patterns. Moreover, benefits of the reductions of electricity demand during peak time have been benchmarked against the current situation in KSA.

6.2 Effectiveness and Large-Scale Deployment of Solution for PV Systems

In relation to PV, this thesis in Chapter 3 has proposed an algorithm for finding optimum tilt and azimuth angles for PV systems matched to the timing of the peak demand on the load profile. The algorithm also takes into account the reduction in the performance of solar PV systems as a result of the accumulation of dust – an extremely important area that has not been analysed so far in the literature on the subject in relation to KSA. The proposed algorithm has been used to study and analyse the prospect of installing solar PV panels in government properties – particularly on the roofs of schools, malls and mosques in residential neighbourhoods – in the city of Riyadh because the residential sector constitutes majority of the electricity consumption of any sector in KSA.

To simplify the analysis, it was assumed that only 500 m^2 of the total roof size of each of the 18,073 mosques in the Riyadh region is used for solar panel installation although the roof sizes of these mosques vary widely from a size of 1,600 m^2 to 21,000 m^2 for some of the most popular mosques (refer to Table 3.2). Accordingly, the combined total of roof areas of the mosques that can be used for solar panel installation is 9,036,500 m^2. Also, given that the total numbers of boys' and girls' government schools in Riyadh are 1151 and 1351 (a total of 2,522), respectively, and the assumed roof area of each of these schools is 1000 m^2 (although, the roof areas of all the schools without including the car park areas range from the minimum of 2000 m^2 to a maximum of 3000 m^2; however, combined with car park roof areas, which are suitable for PV installation and are no less than 500 m^2 in all cases, the available roof areas for any school is at least 1200 m^2), the combined total roof areas of the schools that can be used for solar panel installation is 2,522,000 m^2. The combined total area of the largest malls' roofs in Riyadh city is 2,395,000 m^2. To be more practical, only 50% of the available total roof area of each of these malls is assumed to be suitable for solar panel installation. Accordingly, the combined total roof areas of the malls that will be used for solar panel installation is 1,197,500 m^2. Therefore, the combined total roof area of the malls, mosques and schools is 12,756,000 m^2. With a typical size of a solar panel being 1.6 m^2, this area can take up 7,972,500 number of solar panels. Assuming these solar panels are actually installed on the roofs with each solar panel having a capacity of 300 Wp, the total output peak power that can be generated from these solar panels is approximately 2.4 GWp. It should be noted that this total output peak power that is generated from the solar panels is the maximum amount of power available to support the grid during the peak demand period. With the tilt angle β and the azimuth angle z set to the optimized values of (that is, the results of the 'average of 5 months' values fixed throughout the year for all the solar panels) that will produce the maximum solar energy from a set of PV generation plants installed in Riyadh with a total capacity of 2.4 GWp, the reduction in peak demand that can be achieved range from a minimum of 1,284 MW (in January) to a maximum of 1,891 MW (in June).

6.3 Effectiveness and Large-Scale Deployment of Smart Solution for AC Systems

A large energy saving in energy consumption, and consequently a huge reduction in energy costs, can be achieved by managing and controlling the operation of AC in buildings. Of the several strategies that can be used to achieve such savings for KSA, this research has focused on the operational strategy of the AC. As previously noted, a major contributor to high electricity consumption in KSA is occupant behaviour. It has been reported that approximately 73% of households in KSA turn on their air conditioning systems for more than 10 hours in a day during the summer months (Aldossary, Rezgui & Kwan, 2015). In fact, from the results of the survey given in Chapter 4, this figure is 75% which closely agree with this previously reported value in the literature.

In order to reduce or manage the energy consumption of the growing population trend, this study therefore proposed the use of intelligent (or smart) control of thermostat settings via scheduling and advance control of the operation of AC systems (DSM) on the one hand and via remotely setting the thermostats appropriately by the utilities (DR) approach on the other. Unlike in previous studies on this subject in relation to KSA that did not consider the daily electricity consumption pattern of customers in residential buildings – which is crucial in understanding the short-term and the long-term occupancy behaviour for such buildings since occupancy behaviour is one of the most important causes of inefficiency in energy use, this study carried out a survey that investigated some of the behavioural factors causing high energy consumption in Saudi Arabia’s residential buildings. Also, measurements of household-level electricity consumption from the different types of housing units in KSA were undertaken and a statistical impression of the current occupancy behaviour was obtained. The insights gained from the survey, enabled the development of the proposed practical approaches of reducing energy consumption in KSA’s residential buildings that did not compromise indoor air quality and comfort of occupants.

Accordingly, the total power needed for the whole of Riyadh during the peak-time hour is 20,329 MW and by applying the different AC operation modes that were proposed, the values of total power savings for the residential sector of Riyadh are 5,026, 5,608, and

1,280 MW for Modes 1, Mode 2 and Mode 3, respectively during peak hour. Assuming that only 30% of houses in Riyadh are to move to these solutions (i.e. Modes), the values of total peak demand reduction would be 1,508 MW (17% savings), 1,682 MW (19% savings) and 384 MW (4% savings) for Modes 1, 2 and 3, respectively, during the peak hour. From the results of the analysis, it can be observed that the savings achieved with Mode 2 (the advanced control mode) gives the best energy savings.

Mode 1 and Mode 2 solutions allow the air-conditioning systems to run on a scheduled non-continuous basis. The sensors enable the smart thermostats to learn customers' occupancy behaviour over the periods of the day or week such that energy consumption is reduced during non-occupancy periods. Mode 3 uses the DR approach where the utilities can automatically control the thermostat settings of the air conditioning systems of households if and when appropriate. Consequently, these three approaches do not require daily thoughts or actions from occupants to achieve energy savings. Also, they are realistic and practical as they do not require home occupiers' intervention to change the thermostat settings.

6.4 Effectiveness and Large-Scale Deployment of Solution for SWH Systems

KSA has high potentials for developing energy production via SWH systems, but it has not taken advantage of this technology to a large extent for increasing its energy generation and reducing peak electricity demand so far. This research has presented and analysed the reduction in peak electricity demand achievable when domestic hot water is supplied using SWH systems for KSA. The potential for SWH system to provide energy in the case of KSA will be appraised further in this section.

From the results of Chapter 5, the energy savings that can be accomplished if around 30% of households in Riyadh city (which has 1,116,339 total number of households and is 6,506,700 in population) are to move to SWH systems for the provision of their domestic hot water requirements is 2,094 MWh per day. In particular, the peak hour demand reduction is approximately 51.5 MW where the peak hour is from 14:00 to 15:00 (and the peak time is 14:22).

Because factors such as policy, culture, and energy cost play a great role in the acceptance of SWH technologies (Leidl & Lubitz, 2009), further discussion on how the government in KSA can support the large scale deployment of SWH systems is given in the subsequent paragraphs in the hope that it will encourage the government to popularize the use of SWH systems and encourage their usage.

Many governments around the world have one way or the other initiated incentive programs to encourage the build-up of the application of SWH systems. The increase in the usage of SWH measured by the number of sales of SWH collectors for the case of Taiwan for instance, where the government intervened between 1986 and 1991 and between 2000 and 2007 is illustrated Figure 6.1 (Chang *et al.*, 2009). It is clear from this figure that there was a reduction in the sales of SWH between 1995 and 1999 when government subsidies where removed. Accordingly, it might be difficult to promote SWH systems without government support (Chang *et al.*, 2009).

Financial incentives (such as tax credits and soft loans from the government) and education are some of the factors that have been identified as driving the adoption of SWH systems (Wang *et al.*, 2015). KSA should devise effective financial incentives as well as outreach programmes for educational purposes to speed up its SWH systems deployment rate. To achieve this, it could, for instance, implement the Indian government policy or similar: India's central government, through its Ministry of New and Renewable Energy (MNRE) provides subsidies through soft loans for the installation of SWH systems at an interest rate of 2 – 5 %. This interest rate reduces to 0% for Indian states falling behind in their renewable energy special category (Veeraboina & Ratnam, 2012).

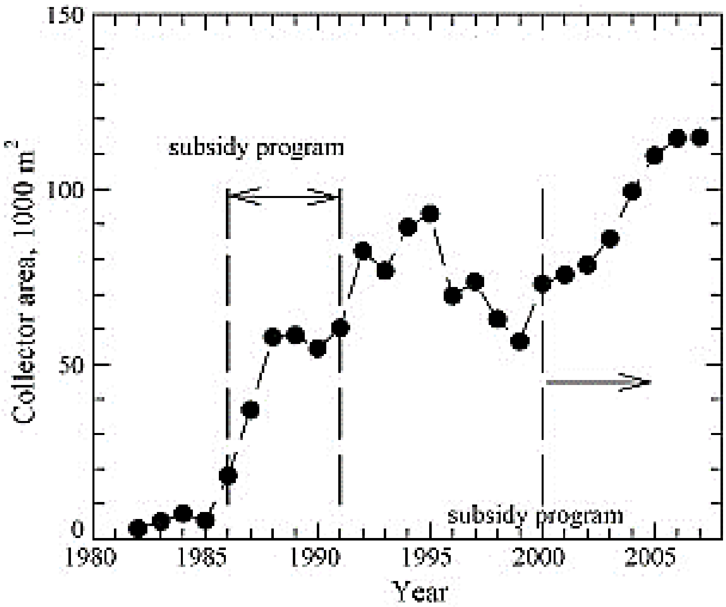


Figure 6.1: Annual sales of SWH systems in Taiwan (Chang *et al.*, 2009)

KSA should encourage managers and owners of hotels and hospitals to adopt SWH. For government buildings, roof availability is not an issue. Moreover, the government can make it compulsory for all new residential homes and public buildings to install SWH systems to provide hot water.

The initial cost of SWH systems can be considerably higher than that of the conventional alternatives. To reduce sales price by reducing the cost of production, KSA could encourage local production of SWH systems since the manufacturing procedure of SWH systems does not require advanced technology (Chang *et al.*, 2009). In fact, according to a research conducted by the King Abdul-Aziz City for Science and Technology (KACST) in 1990s, the final cost of the local fabrication (manufacturing) of SWH systems in KSA is about 70% cheaper than the those that are being imported into the country (Huraib, Hasnain & Alawaji, 1996). It is therefore important for KSA to create enabling environment for indigenous production of solar manufacturing capabilities and products. In particular, KSA can also learn from China's experience of SWH systems: The SWH industry in China has witness a rapid growth in the last few decades. In fact, between 2001 and 2012, annual growth rate of installed SWH systems capacity in China is 20.9% (Luo, Huo & Xie, 2013). Moreover, newly installed SWH systems capacity in China alone in 2011 accounted for 84.0% of the world's installations (Qiu, Ruth & Ghosh, 2015) – refer to Figure 6.2.

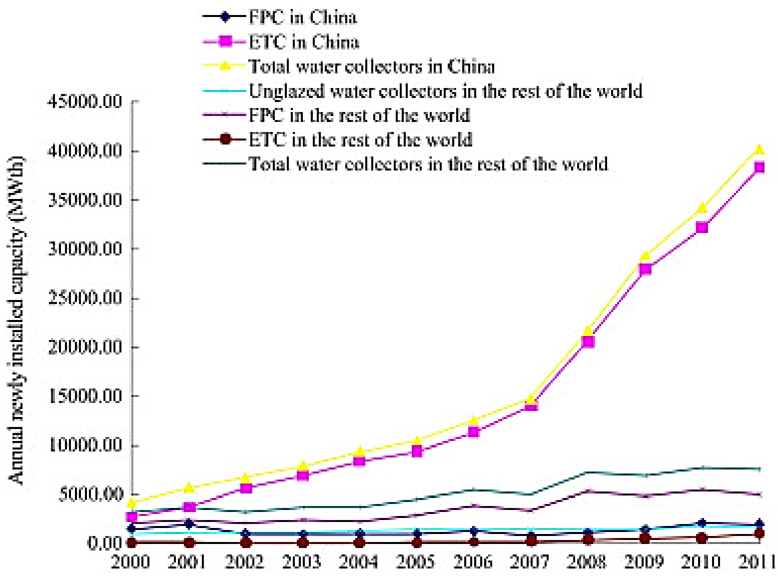


Figure 6.2: Installation of SWH collectors around the world - evacuated tube collectors (ETC) and flat plate collectors (FPC) (Qiu, Ruth & Ghosh, 2015)

The use of evacuated tube collectors (ETC) instead of flat plate collectors (FPC) or other types of collectors for SWH systems in China has been attributed to be the major reason behind China's dominant position in the SWH industry in the world. This has been attributed to China's continuous innovations in research and local manufacturing of the evacuated tube collectors to improve quality and satisfy local consumer needs with as low initial costs and short payback periods as possible. From this perspective, the resistance to adopt flat plate SWH technologies developed in industrialized countries has encouraged the significant adoption of SWH systems in China's households (Qiu, Ruth & Ghosh, 2015) but other factors have also contributed to the Chinese success include favourable government policies, cultural acceptance, high profitability and lack of adequate electricity in some regions (Liu, Liu & others, 2013).

In conclusion, it is recognised that while the contribution of solar thermal is relatively not as pronounced in terms of the amount of energy savings compared to the other measures evaluated in this research, the adoption of SWH offers significant cost savings for households. Its use should, therefore, be heavily promoted in both existing homes and new home developments in order to reduce demand on the national grid during peak hours. For new homes, the government could make it a requirement whenever it would be easily installed. For the existing homes, however, it is recognised that retrofitting this measure to replace many electric heaters would be challenging. In these cases, simple timers set to avoid using of electric heaters during the peak time and the installation of timers would be quick and easy to do. Moreover, the electric heaters are already equipped with storage facility in the cylinder. Finding the representative models of hot water usage profile over the period of the day and across the seasons of the year that are based on statistical data obtained from KSA's households should be subject of future research work in this area.

6.5 Combination of Solutions

In this section, an estimate of total reduction in energy consumption during peak time in the summer months (May to September) that is achievable when the solutions proposed in this study are combined together will be determined.

For solar PV systems, the average total contribution to electric energy generation for the five summer months (obtained by taking the average of monthly average production of Figure 3.18) during the peak hour is 1,891 MW (22% savings from residential peak and 9 % of the electricity requirement during peak time for Riyadh region).

For AC systems, when 30% of houses in Riyadh move to Mode 2 (the mode that gives the best energy savings according to the analyses in Chapter 4), the values of total peak demand reduction is 1,682 MW (19% savings from residential peak and 8 % savings from total peak) during the peak hour.

For SWH systems, the energy savings that can be accomplished when 30% of households in Riyadh city move to SWH systems for the provision of their domestic hot water requirements is approximately 51.5 MW (0.59% savings from residential peak and 0.25 % savings from total peak) during the peak hour.

Applying the same method as has been done for AC and WHS systems where it has been assumed that 30% of the houses in Riyadh can easily adopt these solutions. It is proper here to suppose that 30% of houses can also install PV solar systems on the roofs of the houses as part of the solution to reduce their electricity bills. Based on this, it is assumed that such houses are able to spare 50 m^2 for PV solar systems' installation. According to the Ministry of Municipality in Saudi Arabia (MOMRA-Website, 2017), the average area of a residential sites in KSA is 625 m^2 and residents allowed to build on a maximum of

60% of this land area (i.e. 375 m^2) (Aldossary, Rezgui & Kwan, 2015; Taleb & Sharples, 2011). PV and other renewable energy systems can therefore be conveniently installed on the unused spaces. Moreover, even if the unused spaces are considered unsuitable for such installations (e.g. for aesthetic reasons) or are used for other purposes, the roofs of KSA's built parts of the residential units are flat with the floors made of concrete. The 50 m^2 area of the roofs, which can often range from 100 m^2 to up to 375 m^2 in total area on the average, can be used for solar PV panels' installations. Moreover, houses in Riyadh are built with flat roof tops raised by 1.5 m at the edges (refer to Figure 4.5 to Figure 4.8, for example) so PV panels can conveniently be installed on the roofs. Dedicating 2 to 3 m^2 for the installation of WHS systems is also suitable on the flat roofs. 30% of the total number of houses in Riyadh (i.e. 1,350,249) is 405,075 houses. Therefore, the total area available for PV solar systems' installation is 20,253,750 m^2. Given that the typical size of a solar PV panel is 1.6 m^2, then 12,658,594 number of solar panels will fill the roof spaces of 30% of houses in Riyadh. With each solar panel having a capacity of a value of 300 Wp, the total output peak power that can be generated from these solar panels is 3,797,578,200 Wp or approximately 3.8 GWp.

It should be recalled that, on the analysis of the 2.4 GWp plant in Chapter 3, the PV panels where set to the tilt angle β and the azimuth angle z set to the optimized values (that is, 'average of 5 months' values fixed throughout the year) and produces energy from a minimum of 1,284 MW (in January) to a maximum of 1,891 MW (in June) when the effect of dust has been taken into account; therefore, the average total contribution to electricity generation during the 5 summer months during the peak hour is 1,891 MW. Using the same method of analysis, the minimum and maximum values for the 3.8 GWp are 2,033 MW in January and 2,994 MW in June, respectively, and the average total contribution to electricity generation during the 5 summer months during the peak hour is 2,994 MW (15% of the total power requirement during peak time).

The total reduction obtained by combining each of the solutions (1,891 MW from PV systems from government buildings 1,682 MW from AC systems, 51.5 MW from SWH systems and 2,994 MW from PV systems from houses) is 6,619 MW. Given that the total power needed for the whole of Riyadh region (of which Riyadh city is part) during the peak time is 20,329 MW, the application of the combined solution is able to effectively reduce this demand by 33%. The annual clean energy from 6,619 MW is 14,495 GWh ($Energy(MWh) = Wp \times sun\,peak\,hour\ in\ KSA \times 365$), this amount of clean energy represents 11.8 $MtCO_2$ emissions annually, (0.816 t/MWh CO2 emission factor for Saudi Arabia) (Mansouri, Crookes & Korakianitis, 2013). Therefore, the implementation of these proposed solutions would be beneficial for the nation's economy and reduce dependency on fossil fuels and improve the condition of the global climate environment. In practice, it is unlikely that a simple sum of these outcomes can be used to calculate the total energy reduction because of the different policy measures that would be needed to stimulate them, and the different timescales of rollout. A summary of the combination of the proposed solutions is given in Table 6.1.

Table 6.1: Summary of average reduction in electricity consumption achievable during peak time in the summer months

Description of Energy Source	Amount of Average Power Production or Saving in Summer	Corresponding % of Power Requirement of Riyadh Region During Peak Time
solar PV systems installing on government buildings (schools, malls and mosques)	1,891 MW	9 %
Solar PV with 30% of households in Riyadh moved to solar PV systems	2,994 MW	15 %
AC systems with 30% of households in Riyadh city moved to Mode 2 of AC operation	1,682 MW	8.3%
SWH systems with 30% of households in Riyadh moved to SWH systems	51.5 MW	0.25 %
TOTAL	**6,619 MW**	**33%**

KSA has embarked on a project code-named "Vision 2030" – announced in April 2016 – whose aim is to modernize and diversity its economy by exploiting its strategic location and connection to three continents (Asia, Europe and Africa) and in view of the role the kingdom plays in the Islamic and the Arab world (Fattouh & Sen, 2016; Ichord, 2018). In order to realize its Vision 2030 ambition, programmes that have been announced includes the National Transformation Program (NTP), the Financial Sector Development Program, the Quality of Life Program, the Privatisation Program, the Public Investment Fund Program, and the Fiscal Balance Program (Vision-2030-Website, 2018). As at the time of writing this thesis, details about the implementation of these programmes were only just beginning to slowly emerge. The paragraphs that follow present and discuss some of these details that are related to the theme of this thesis on renewable energy.

KSA depends on oil for electricity generation and this cuts significantly into its oil export capacity (Ichord, 2018). In fact, if domestic oil consumption continues to increase at the current annual increase rate, it is predicted that the kingdom will be a net oil-importing country by the late 2030s (Yamada, 2016). As part of the NTP programme of Vision 2030, the government has tasked King Abdullah City for Atomic and Renewable Energy (KACARE) with meeting the strategic objectives of enabling renewable energy to actively contribute in the national energy mix and of increasing the local content in the industrial and service value chains and localization of expertise in renewable energy technologies, among others (Qualex, 2018; Vision-2030-Website, 2030). With this, it aims to diversify its power generation base and pursue alternative generation sources such as renewable energy sources.

Also, the government aims to improve energy efficiency use by reducing or removing subsidies. Importantly, due to heavy air conditioning load, the residential sector is a key target for this subsidy reduction and removal. However, the country still faces a huge challenge to bring dependence on oil for electricity generation under control. These challenges, for example, include the need to provide fresh water to the population and for industrial plants' use by the thirty desalination plants of the kingdom which require a huge amount of electricity from the oil-based generation plants (Ichord, 2018).

In addition, in order to meet its growing demand for electricity and move away from an oil-dependent economy, the kingdom is to build 3.45 GW of renewable energy plant by 2020 and to add 6 GW to this by 2023 (Qualex, 2018). It has already been announced that a 300 MW solar PV plant will be built in Sakaka and 2.4 GW wind energy plants will be constructed in Midyan and Dumat Al-Jandal as part of the 3.45 GW renewable energy target. Since 2018, with the aim of creating a globally competitive local industry, government projects on renewable energy require proof of 40% local content which, for example, means that to bid for a project in solar plant systems, bidders will have to prove that 40% of the components of the systems will be manufactured in KSA (Scott, 2018). The bid of the 300 MW project has already been won by ACWA and Masdar (Ichord, 2018). Also, as part of the 2020 targets of the NTP programme, KSA intends to increase the local content contribution within the renewable energy sector from 25% to 35%, The legal and regulatory framework for the deployment of small-scale solar energy systems (i.e. solar systems with generating capacity less than 2 MW) has recently been published by KSA's Electricity and Co-Generation Regulatory Authority in August 2017 and its enforcement started in July 2018 (ECRA-Website, 2017). The framework prescribes policies governing electricity consumers that want to operate their own solar plant and export their unused or excess power to the national grid.

Despite the ambition to generate a total of 9.4 GW from renewable energy sources by 2023, this amount of generation only constitute approximately 10% of the current total generating capacity. The fact that the energy demand of the population continues to increase at the rate of 6% of the installed capacity annually, it is unlikely that the current policy alone will be sufficient to significantly increase the amount of energy from renewable sources to the national grid.

However, as the results of this thesis have shown, installing solar PV systems on government buildings in Riyadh city alone, whose peak time demand is 5.496 GW, can generate up to 1.891 GW (34% of the requirement) electricity during the peak time. Better control of AC systems (using Mode 2, for example) on the part of, at least, 30 % of Riyadh electricity customers will yield 0.69 GW in electricity savings (11 % of the requirement) during peak time. In other words, the installation of PV solar systems on government buildings only and the more efficient use of AC in 30% of Riyadh's residential buildings can reduced the required energy production from traditional oil and gas sources by 45%. Moreover, Riyadh is just one of the four regions in KSA and the implementation of the proposed solutions of this study can be expanded to these regions of KSA. In fact, some authors, such as (Ichord, 2018), have argued that KSA can only meet its energy demand via plants fired by oil and gas for the foreseeable future with the current policy and implementation of Vision 2030. This author therefore argues that KSA can meet its energy demand with less reliance on oil and gas and certainly beyond the year 2030 by expanding its ambition to include the solutions proposed in this thesis. The implementation of a small part of the Vision 2030 plan is a first step (and demonstrates the government seriousness on this issue) but it is necessary and possible to further expand the scope of government policies through ambitious programmes that will exploit the aforementioned proposed solutions.

Chapter 7: Conclusion, Recommendations and Future Work

7.1 Conclusion

The overall objective of the present work is to investigate and compare the most applicable solutions to mitigate the peak electricity demand of the residential sector that conform to national strategies and policies of KSA. In order to achieve the research aim, the proposed applicable solutions took advantage of renewable energy technologies and integrated smart grid options. The main contributions of this study are summarized here.

An algorithm for finding optimum tilt and azimuth angles for PV systems matched to the timing of the peak demand on the load profile is proposed. The proposed algorithm also takes into account the reduction in the performance of solar PV systems as a result of the accumulation of dust (which can have detrimental impact on the output of PV systems) – an extremely important area that has so far been neglected in the literature on the subject in relation to KSA and other countries with similar desert-like environment. Consequently, the novelty in the proposed algorithm is the matching of the optimization of the tilt and azimuth angles to the load profile and the inclusion of dust accumulation effects into the algorithm in order to compute the optimum tilt and azimuth angles that will enable the extraction of the high amount of the solar radiation that is harvestable.

Using the proposed algorithm, numerical results for the case of Riyadh city in KSA were given. The problem of finding the optimal tilt angle β and azimuth angle z that gives the maximum solar energy from a set of PV generation plants with a given total capacity and inverter efficiency in the city of Riyadh was investigated. The practical case of installing PV panels in government building (malls, schools and mosques) in residential was considered. It was assumed that a fixed portion of the total roof area of each of the 18,073 mosques, 2,522 government schools and 51 malls in the Riyadh region is used for solar panel installation, and with a typical size of a solar panel of 300 Wp capacity being 1.6 m^2, the combined total of roof areas of these that can be used for solar panel installation is estimated. From this value, the total output peak power that can be generated from these solar panels is obtained. With the tilt angle β and the azimuth angle z set to the optimized values, the reduction in peak demand that can be achieved is obtained.

Also, PV and other renewable energy systems can be conveniently installed on the unused spaces of roofs of houses in residential areas of KSA. Moreover, the roofs of KSA's built parts of the residential units are flat with the floors that are made of concrete. The 50 m^2 area of the roofs, which can often range from 100 m^2 to up to 375 m^2 in total area on the average, when used for solar PV panels' installations can contribute a huge amount of electricity generation for the country. According to the results presented in this thesis, for example, if only 30% of the houses in the city of Riyadh were to install PV systems on 50 m^2 area of their roofs, the total average contribution to electricity generation during the 5 summer months during the peak hour is up to 15% of the electricity requirement during peak time for Riyadh region.

A good energy saving (for example, 28% of all houses in Riyadh) and, consequently, a huge reduction in energy costs can be achieved by managing and controlling the operation of AC in buildings. The behaviour of building occupants, which is very important for scheduling the buildings' climate control, is one of the most important factors influencing the buildings dynamic thermal properties and also one of the most difficult to develop a model for. Such models are needed for computer simulation of the energy consumption of KSA's residential buildings in order to propose solutions that will make savings as a result of energy consumption of AC systems achievable. In this respect, a survey is carried out in this research to understand occupancy behaviour such as times of rooms' occupation and usage of electricity consumption appliances. Also, physical measurements of household-level electricity consumption from the different types of housing units in KSA are taken and a statistical inference of the current occupancy behaviour was obtained. This is the first attempt to describe occupancy behaviour of residents of KSA to the author's knowledge. The insight gained from the survey is then used for the computer simulation of residential buildings' energy performance to understand the energy savings possible if AC systems are used in a more energy efficient manner.

Three modes of air-conditioning systems' operation are proposed in this research. Of these, two modes fall into the Demand-Side Management (DSM) category of electricity management strategy while the third mode falls into the Demand Response (DR) category. For modes running on the DSM paradigm, air-conditioning systems run on a non-continuous and scheduled basis; smart thermostats that are able to learn customers' occupancy behaviour are installed such that energy consumption is reduced during non-occupancy periods, over the periods of the day or week. Moreover, such thermostats are also equipped with features for pre-cooling periods which start the air-conditioning systems prior to room occupation depending on the thermal mass of the building and the capacity of the air conditioning unit relative to the heat load. For the mode running on the DR approach, the utilities can remotely set the thermostats of the AC systems to 24^{o}C during peak hours.

In the past, most countries of the Gulf Cooperation Council (GCC) have not had policies that seriously encourage the usage of solar thermal systems. This study presents and analysed the reduction in peak electricity demand achievable when domestic hot water is supplied using solar water heating (SWH) systems for KSA. The kingdom has high potentials for developing energy production via SWH systems, but it has not taken advantage of this technology to a large extent for increasing its energy generation and reducing peak electricity demand so far. The potential for SWH system to provide energy in KSA is therefore appraised. Conclusions were drawn for KSA and Riyadh city in particular based on theoretical and physical measurements that were taken. The energy savings that can be accomplished if a fixed percentage of households in Riyadh city (with a total population of 6,506,700) are to move to SWH systems for the provision of their domestic hot water requirements are studied. In particular, the peak hour demand reduction is determined. The results were compared with a previous study for Oman – a country similar to KSA in climate, culture and energy usage. The computed values for Riyadh presented in this study appear to be more realistic.

Finally, this study presents an estimate of total reduction in energy consumption during peak time in the summer months (May to September) that is achievable when all the solutions proposed in this study are combined together.

7.2 Recommendations

From this study therefore, a list of recommendation in relation to mitigating the challenge of electricity consumption in KSA are as follows:

1. KSA's policy makers and stakeholders should deploy solar PV systems on government buildings and actively promote households to do the same. As has been shown in this thesis for the case of Riyadh city, the installation of solar systems in government buildings in Riyadh city alone can generate up to 9% of the kingdoms' total electricity during peak demand periods of the summer months. In addition, this reaches up to 23% of the country's demand if up to 30% of Riyadh households adopt solar PV systems for meeting their electricity needs.
2. In order to promote the installation of PV solar system in households in KSA, the cost of purchase and installation of PV solar systems in households should be subsidized. The utility companies, for example, could also offer discount to customers who install solar PV systems in their homes.
3. In order to achieve the much needed saving in energy consumption by AC systems in the residential sector, the electricity policy makers and stakeholders can encourage both utility companies and residents to use AC smart control in the context of DSM. Utility companies can be given a period of time to ensure that a percentage of their customers deploy AC systems equipped with smart scheduling and control in their house and increase this percentage gradually. Moreover, the companies that provide these technologies can be supported through facilities such as tax reduction or tax relief.
4. To reduce the AC consumption during the peak time, utility companies should encourage their customers to reduce their energy use during peak time by subscribing to a DR scheme to let the companies control some or most of their AC units during the peak time period
5. In order to encourage the use of SWH systems, KSA's stakeholders and policy makers can provide financial incentives for their adoption. These financial incentives could be in the form of tax credits and soft loan (for example, with interest rate as low as 0%) from the government. The stakeholders must also

develop outreach programmes for educational purposes to speed up the awareness and the adoption of SWH systems to reduce household electricity bills.

6. KSA government, through financial incentives such as tax reduction, should encourage managers and owners of hotels and hospitals to adopt SWH systems. The government can make it compulsory for all new government building projects to depend solely on SWH systems except in the case of emergencies.

7.3 Future Work

Research in finding solutions to the growing energy needs, particularly the challenges associated with the demand during the peak time, in KSA is still on-going and there are still many areas to explore. Based on the findings of this thesis, the areas in which future research on this subject should focus on are summarized in the paragraphs that follow.

In using the algorithm proposed in Chapter 3: for finding the optimum tilt and azimuth angles while taking into account the effects of dust, the reduction in solar radiation on the PV panels due to the transmittance reduction was based on limited data available for Cairo (Egypt) and for an observation of a limited time of seven months due to lack of availability of data for Riyadh city. Measurements of transmittance reduction and rate of dust accumulation/removal need to be undertaken for Riyadh city and, more generally, KSA in order to arrive at more accurate optimum angles for Riyadh and, more generally, any location for which the proposed algorithm will be applied to. Future research should also look into technologies for avoiding dust accumulation on PV systems as it poses a huge challenge in harnessing maximum energy from these systems. Studies should also be carried out on the cost and optimum cleaning frequency of PV panels to prevent dust accumulation on PV systems that are currently available in the market. Future studies should also extend to finding the safest and cheapest cleaning methods and technologies.

Central to achieving smart control of AC are the use of sensors. To achieve the level of savings obtained in this study however, the residential buildings require sensors that are able to detect occupancy with high degree of accuracy in order to obtain the schedule that can be updated periodically. Occupancy sensor technologies is an area of on-going research and future work should focus in the development of cheap occupancy sensors of high accuracy without the challenges of privacy and data intrusiveness. More generally, future work should also look into other types of domestic appliances, in addition to AC systems, that will be good candidates that can provide DR in order to achieve even larger amount of energy savings. Moreover, three modes of AC operation have been investigated in this research. It would be worthwhile to investigate the energy savings achievable with other different techniques of controlling AC based on occupancy behaviour obtained through high accuracy occupancy sensors. In addition, future work can investigate the extension of the modes of AC operations proposed for the residential sector in this study to government buildings, such as mosques and schools, and to other sectors. Mosques and schools, in particular, because they are opened only during specific times of the day, can consider relying exclusively on renewable energy sources during peak energy demand periods.

A model of hot water consumption derived from a UK survey has been used for building hot water consumption in KSA with the justification that it gives values consistent with measured consumption in typical homes in Riyadh. The amount and distribution of domestic hot water use in Riyadh may, in reality, vary from the assumptions employed here given the difference in culture, energy policy and energy cost of the two countries. Future research work in this area should focus on finding models that are based on statistical data obtained from KSA's households as, currently, no such data exists on the water consumption (in general, and hot water in particular) for households in KSA. Importantly, as KSA is a sunny country, investigation should be carried out on the possibility of moving all households' hot water requirement to SWH systems.

Finally, in this study, analyses of the solutions proposed for managing the peak electricity demand that is largely due to the high level of energy consumption in the residential sector were carried out for Riyadh city by estimating the potential energy savings through the electricity generation via renewable energy technologies and through the reduction of energy consumption in the residential sector during the peak period. The climate is generally desert-like in Saudi Arabia, therefore, a reasonable amount of energy and corresponding fossil fuels could be saved by expanding the proposed solutions to include other KSA's regions and cities. Future work should extend the findings to the whole of KSA and, possibly, other countries, particularly those in the Middle East, with similar climatic conditions and electricity usage behaviour and patterns. Benefits of the reductions of electricity demand during peak time should be benchmarked against the results of this study.

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Appendices

Appendix A: Matlab Code

1. Matched' case using 'fmincon'

```
global  omega_sunrise_i omega_sunset_i delta_deg phi omega_i...
        sinAlpha B D generation Ta eps

% (15° is equivalent to one hour)
omega_i(12) = -35.4285; % Offset for Azimuth at 30 deg.
for i = 1:11
    omega_i(i) = -(12 - i)*15 - 35.4285;
end
for i = 13:24
    omega_i(i) = (i - 12)*15 - 35.4285;
end

phi = 24.633;
if phi > 45
    e_c = 0.65;
else
    e_c = 0.75;
end

Ho = 1.367;

Jan = cell(1,31); for n=1:31, Jan{n}=num2str(n); end
Feb = cell(1,28); for n=32:59, Feb{n}=num2str(n); end
```

```
Mar = cell(1,31); for n=60:90, Mar{n}=num2str(n); end
Apr = cell(1,30); for n=91:120, Apr{n}=num2str(n); end

May = cell(1,31); for n=121:151, May{n}=num2str(n); end
Jun = cell(1,30); for n=152:181, Jun{n}=num2str(n); end
Jul = cell(1,31); for n=182:212, Jul{n}=num2str(n); end
Aug = cell(1,31); for n=213:243, Aug{n}=num2str(n); end

Sep = cell(1,30); for n=244:273, Sep{n}=num2str(n); end
Oct = cell(1,31); for n=274:304, Oct{n}=num2str(n); end
Nov = cell(1,30); for n=305:334, Nov{n}=num2str(n); end
Dec = cell(1,31); for n=335:365, Dec{n}=num2str(n); end

days = 365;             % Days in a year

% 'fmincon' parameters:
lb = [-20,-10];
ub = [70,10];

eps = -0.0044;

% ~~~~~~~~~~~~~~~~~~~~~~~~~~~
for n = 1:days;
    delta_deg = 23.45 * sind(360*(mod(284+n,365))/365);
    delta_rad = deg2rad(delta_deg);

    % Solar radiation power: sin(alpha)
       omega_sunset = acosd(-tand(phi)*tand(delta_deg));
```

```
    i = 1;
    while (omega_i(i) < -omega_sunset)
        i = i + 1;
        if i == 25
            i = i - 1;
            break
        end
    end
    omega_sunrise_s = -omega_sunset;
    omega_sunrise_i = i;

    i = 1;
    while (omega_i(i) < omega_sunset)
        i = i + 1;
        if i == 25
            i = i - 1;
            break
        end
    end
    omega_sunset_s = omega_sunset;
    omega_sunset_i = i;

    sinAlpha = zeros(1,24);
    for i = omega_sunrise_i : omega_sunset_i
        sinAlpha(i) = sind(delta_deg)*sind(phi) + cosd(delta_deg)*...

cosd(phi)*cosd(omega_i(i));
```

```
        if sinAlpha(i) < 1e-7
            sinAlpha(i) = 0;
        end
    end

    N = omega_sunset_i - omega_sunrise_i;      maxSunHours = N;
    r = num2str(n);
    switch (r)
        case Jan, index = 7/11;  Ta = 19;
        case Feb, index = 8/11;  Ta = 22;
        case Mar, index = 7/11;  Ta = 26;
        case Apr, index = 8/11;  Ta = 32;

        case May, index = 9/11;  Ta = 38;
        case Jun, index = 11/11; Ta = 41;
        case Jul, index = 11/11; Ta = 42;
        case Aug, index = 10/11; Ta = 42;

        case Sep, index = 9/11; Ta = 40;
        case Oct, index = 10/11;  Ta = 34;
        case Nov, index = 9/11;  Ta = 27;
        case Dec, index = 7/11;  Ta = 21;
    end

    sunshineHours = index * maxSunHours;

    % Clearness index for the day
    s = sunshineHours;  % Number of sunshine hours in the day
```

```
    K = e_c*(s/N)^(1/3);


    B = 1.11*Ho*K^2;        % B - Solar beam energy

    D = Ho*K - B;           % D - Solar diffuse energy


    beta_0 = 15; z_0 = 3;

    initial_0 = [beta_0 z_0];


    %    [optimal,    val_optimal]    =    fminunc(@myfunction_ex02,
beta_0,options);

    [optimal, val_optimal] = fmincon(@myfunction_ex02_v3,...

initial_0,[],[],[],[],lb,ub);


    % beta_optimal(n) = optimal;

    beta_optimal(n) = optimal(1); z_optimal(n) = optimal(2);

    year_gen(n,:) = generation;


    max_generation(n) = max(generation);


end
```

2. Optimization for no. 1: myfunction_ex02

```
function g = myfunction_ex02_v3(parameters)


beta_deg = parameters(1);

z = parameters(2);


global  omega_sunrise_i omega_sunset_i delta_deg phi...

        omega_i sinAlpha B D generation Ta eps


% Calculate rb (the effect of beta on incident beam radiation)


for i = omega_sunrise_i : omega_sunset_i

    num = cosd(phi - beta_deg)*cosd(delta_deg)*cosd(omega_i(i) - z*sind(beta_deg)) + sind(delta_deg)*sind(phi - beta_deg);

    den = sind(delta_deg)*sind(phi) + cosd(delta_deg)*cosd(phi)*cosd(omega_i(i));

    rb(i) = num/den;

end


for i = 1:24

    if (i < 9) || (i > 19)

        rb(i) = 0;

    elseif (i < omega_sunrise_i) || (i >= omega_sunset_i)

        rb(i) = 0;

    end

end


invEff = 0.98;
```

```
capacityKWp = 2400000;

for i = 1:24

    rd = 0.5*(1 + cosd(beta_deg));

    generation(i) = invEff * capacityKWp * sinAlpha(i) *...

                    ((B * rb(i)) + (D * rd)) * (1+ eps * (Ta - 25));

end




g = -sum(generation);
```

3. Average of 5 months

```
omega_i(12) = -35.4285; % Offset for Azimuth at 30 deg.
for i = 1:11
    omega_i(i) = -(12 - i)*15 - 35.4285;
end
for i = 13:24
    omega_i(i) = (i - 12)*15 - 35.4285;
end

phi = 24.633;
if phi > 45
    e_c = 0.65;
else
    e_c = 0.75;
end

Ho = 1.367;

% Days/Months of the Year
Jan = cell(1,31); for n=1:31, Jan{n}=num2str(n); end
Feb = cell(1,28); for n=32:59, Feb{n}=num2str(n); end
Mar = cell(1,31); for n=60:90, Mar{n}=num2str(n); end
Apr = cell(1,30); for n=91:120, Apr{n}=num2str(n); end

May = cell(1,31); for n=121:151, May{n}=num2str(n); end
Jun = cell(1,30); for n=152:181, Jun{n}=num2str(n); end
Jul = cell(1,31); for n=182:212, Jul{n}=num2str(n); end
Aug = cell(1,31); for n=213:243, Aug{n}=num2str(n); end
```

```
Sep = cell(1,30); for n=244:273, Sep{n}=num2str(n); end
Oct = cell(1,31); for n=274:304, Oct{n}=num2str(n); end
Nov = cell(1,30); for n=305:334, Nov{n}=num2str(n); end
Dec = cell(1,31); for n=335:365, Dec{n}=num2str(n); end

days = 365
eps = -0.0044;
for n = 1:days;
    delta_deg = 23.45 * sind(360*(mod(284+n,365))/365
    delta_rad = deg2rad(delta_deg);


    omega_sunset = acosd(-tand(phi)*tand(delta_deg));

    i = 1;
    while (omega_i(i) < -omega_sunset)
        i = i + 1;
        if i == 25
            i = i - 1;
            break
        end
    end
    omega_sunrise_s = -omega_sunset;
    omega_sunrise_i = i;

    i = 1;
    while (omega_i(i) < omega_sunset)
```

```
        i = i + 1;
        if i == 25
            i = i - 1;            break
        end
    end
    omega_sunset_s = omega_sunset;
    omega_sunset_i = i;

    sinAlpha = zeros(1,24);
    for i = omega_sunrise_i : omega_sunset_i
        sinAlpha(i)        =        sind(delta_deg)*sind(phi)        +
cosd(delta_deg)*cosd(phi)*cosd(omega_i(i));
        if sinAlpha(i) < 1e-7
            sinAlpha(i) = 0;
        end
    end

    N = omega_sunset_i - omega_sunrise_i;
    maxSunHours = N;
    r = num2str(n);
    switch (r)
        case Jan, index = 7/11;  Ta = 19;
        case Feb, index = 8/11;  Ta = 22;
        case Mar, index = 7/11;  Ta = 26;
        case Apr, index = 8/11;  Ta = 32;

        case May, index = 9/11;  Ta = 38;
        case Jun, index = 11/11; Ta = 41;
```

```
        case Jul, index = 11/11; Ta = 42;

        case Aug, index = 10/11; Ta = 42;


        case Sep, index = 9/11; Ta = 40;

        case Oct, index = 10/11;  Ta = 34;

        case Nov, index = 9/11;  Ta = 27;

        case Dec, index = 7/11;  Ta = 21;

    end


    sunshineHours = index * maxSunHours;


    s = sunshineHours;  % Number of sunshine hours in the day

    K = e_c*(s/N)^(1/3);




    B = 1.11*Ho*K^2;

    D = Ho*K - B;


    AVG_max_of_summer = 2.3559;

    beta_deg = AVG_max_of_summer;

    z = 0.5882;


    for i = omega_sunrise_i : omega_sunset_i

        num = cosd(phi - beta_deg)*cosd(delta_deg)*cosd(omega_i(i) -
z*sind(beta_deg)) + sind(delta_deg)*sind(phi - beta_deg);

        den          =          sind(delta_deg)*sind(phi)          +
cosd(delta_deg)*cosd(phi)*cosd(omega_i(i));

        rb(i) = num/den;
```

```
    end



    for i = 1:24
        if (i < 9) || (i > 19)
            rb(i) = 0;
        elseif (i < omega_sunrise_i) || (i >= omega_sunset_i)
            rb(i) = 0;
        end
    end

    invEff = 0.98;
    capacityKWp = 2400000;
    for i = 1:24
        rd = 0.5*(1 + cosd(beta_deg));
        generation(i) = invEff * capacityKWp * sinAlpha(i) *...
            ((B * rb(i)) + (D * rd)) * (1+ eps * (Ta - 25));
    end
    max_generation(n) = max(generation);

    year_gen_notoptimal(n,:) = generation;

end
```

4. Year Best Angles.

```
omega_i(12) = -35.4285;
for i = 1:11
    omega_i(i) = -(12 - i)*15 - 35.4285;
end
for i = 13:24
    omega_i(i) = (i - 12)*15 - 35.4285;
end


phi = 24.633;
if phi > 45
    e_c = 0.65;
else
    e_c = 0.75;
end


Ho = 1.367;
Jan = cell(1,31); for n=1:31, Jan{n}=num2str(n); end
Feb = cell(1,28); for n=32:59, Feb{n}=num2str(n); end
Mar = cell(1,31); for n=60:90, Mar{n}=num2str(n); end
Apr = cell(1,30); for n=91:120, Apr{n}=num2str(n); end


May = cell(1,31); for n=121:151, May{n}=num2str(n); end
Jun = cell(1,30); for n=152:181, Jun{n}=num2str(n); end
Jul = cell(1,31); for n=182:212, Jul{n}=num2str(n); end
Aug = cell(1,31); for n=213:243, Aug{n}=num2str(n); end


Sep = cell(1,30); for n=244:273, Sep{n}=num2str(n); end
```

```
Oct = cell(1,31); for n=274:304, Oct{n}=num2str(n); end

Nov = cell(1,30); for n=305:334, Nov{n}=num2str(n); end

Dec = cell(1,31); for n=335:365, Dec{n}=num2str(n); end


days = 365

eps = -0.0044;


for n = 1:days

    delta_deg = 23.45 * sind(360*(mod(284+n,365))/365);

    delta_rad = deg2rad(delta_deg);


    omega_sunset = acosd(-tand(phi)*tand(delta_deg));


    i = 1;

    while (omega_i(i) < -omega_sunset)

        i = i + 1;

        if i == 25

            i = i - 1;

            break

        end

    end

    omega_sunrise_s = -omega_sunset;

    omega_sunrise_i = i;


    i = 1;

    while (omega_i(i) < omega_sunset)

        i = i + 1;

        if i == 25
```

```
            i = i - 1;
            break
        end
    end
    omega_sunset_s = omega_sunset;
    omega_sunset_i = i;

    sinAlpha = zeros(1,24);
    for i = omega_sunrise_i : omega_sunset_i
        sinAlpha(i)        =        sind(delta_deg)*sind(phi)        +
cosd(delta_deg)*cosd(phi)*cosd(omega_i(i));
        if sinAlpha(i) < 1e-7
            sinAlpha(i) = 0;
        end
    end

    N = omega_sunset_i - omega_sunrise_i;
    maxSunHours = N;
    r = num2str(n);
    switch (r)
        case Jan, index = 7/11;  Ta = 19;
        case Feb, index = 8/11;  Ta = 22;
        case Mar, index = 7/11;  Ta = 26;
        case Apr, index = 8/11;  Ta = 32;

        case May, index = 9/11;  Ta = 38;
        case Jun, index = 11/11; Ta = 41;
        case Jul, index = 11/11; Ta = 42;
```

```
        case Aug, index = 10/11; Ta = 42;


        case Sep, index = 9/11; Ta = 40;

        case Oct, index = 10/11;  Ta = 34;

        case Nov, index = 9/11;  Ta = 27;

        case Dec, index = 7/11;  Ta = 21;

    end


    sunshineHours = index * maxSunHours;


    s = sunshineHours;

    K = e_c*(s/N)^(1/3);


        B = 1.11*Ho*K^2;

    D = Ho*K - B;


    BEST_of_year = -5.7931;

    beta_deg = BEST_of_year;

    z = 10;


    for i = omega_sunrise_i : omega_sunset_i

        num = cosd(phi - beta_deg)*cosd(delta_deg)*cosd(omega_i(i) -
z*sind(beta_deg)) + sind(delta_deg)*sind(phi - beta_deg);

        den          =          sind(delta_deg)*sind(phi)          +
cosd(delta_deg)*cosd(phi)*cosd(omega_i(i));

        rb(i) = num/den;

    end
```

```
    for i = 1:24
        if (i < 9) || (i > 19)
            rb(i) = 0;
        elseif (i < omega_sunrise_i) || (i >= omega_sunset_i)
            rb(i) = 0;
        end
    end

    invEff = 0.98;
    capacityKWp = 2400000;
    for i = 1:24
        rd = 0.5*(1 + cosd(beta_deg));
        generation(i) = invEff * capacityKWp * sinAlpha(i) *...
            ((B * rb(i)) + (D * rd)) * (1+ eps * (Ta - 25));
    end
    max_generation(n) = max(generation);

    year_gen_notoptimal(n,:) = generation;

end
```

5. Dust Case

```
global    omega_sunrise_i  omega_sunset_i  delta_deg  phi  omega_i
sinAlpha...
        B D generation c_0 c_1 c_2 c_3 Ta eps


omega_i(12) = -35.4285;.
for i = 1:11
    omega_i(i) = -(12 - i)*15 - 35.4285;
end
for i = 13:24
    omega_i(i) = (i - 12)*15 - 35.4285;
end

phi = 24.633
if phi > 45
    e_c = 0.65;
else
    e_c = 0.75;
end

Ho = 1.367;
```

```
Jan = cell(1,31); for n=1:31, Jan{n}=num2str(n); end
Feb = cell(1,28); for n=32:59, Feb{n}=num2str(n); end
Mar = cell(1,31); for n=60:90, Mar{n}=num2str(n); end
Apr = cell(1,30); for n=91:120, Apr{n}=num2str(n); end

May = cell(1,31); for n=121:151, May{n}=num2str(n); end
Jun = cell(1,30); for n=152:181, Jun{n}=num2str(n); end
Jul = cell(1,31); for n=182:212, Jul{n}=num2str(n); end
Aug = cell(1,31); for n=213:243, Aug{n}=num2str(n); end

Sep = cell(1,30); for n=244:273, Sep{n}=num2str(n); end
Oct = cell(1,31); for n=274:304, Oct{n}=num2str(n); end
Nov = cell(1,30); for n=305:334, Nov{n}=num2str(n); end
Dec = cell(1,31); for n=335:365, Dec{n}=num2str(n); end

days = 365;
lb = [-20,-10];
ub = [70,10];

eps = -0.0044;
for n = 1:days;
    delta_deg = 23.45 * sind(360*(mod(284+n,365))/365);
    delta_rad = deg2rad(delta_deg);

    omega_sunset = acosd(-tand(phi)*tand(delta_deg));
```

```
i = 1;
while (omega_i(i) < -omega_sunset)
    i = i + 1;
    if i == 25
        i = i - 1;
        break
    end
end
omega_sunrise_s = -omega_sunset;
omega_sunrise_i = i;

i = 1;
while (omega_i(i) < omega_sunset)
    i = i + 1;
    if i == 25
        i = i - 1;

        break
    end
end
omega_sunset_s = omega_sunset;
omega_sunset_i = i;

sinAlpha = zeros(1,24);
for i = omega_sunrise_i : omega_sunset_i
    sinAlpha(i) = sind(delta_deg)*sind(phi) + cosd(delta_deg)*...
```

```
cosd(phi)*cosd(omega_i(i));
        if sinAlpha(i) < 1e-7
            sinAlpha(i) = 0;
        end
    end




N = omega_sunset_i - omega_sunrise_i;
    maxSunHours = N;
    r = num2str(n);

switch (r)

        case Jan, index = 7/11; c_0 = 0.2887; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 19;
        case Feb, index = 8/11; c_0 = 0.2727; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 22;
        case Mar, index = 7/11; c_0 = 0.2647; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 26;
        case Apr, index = 8/11; c_0 = 0.3207; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 32;

        case May, index = 9/11;  c_0 = 0.3367; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 38;
        case Jun, index = 11/11; c_0 = 0.2567; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 41;
```

```
        case Jul, index = 11/11; c_0 = 0.2887; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 42;
        case Aug, index = 10/11; c_0 = 0.2567; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 42;

        case Sep, index = 9/11;  c_0 = 0.2567; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 40;
        case Oct, index = 10/11; c_0 = 0.2407; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 34;
        case Nov, index = 9/11;  c_0 = 0.2167; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 27;
        case Dec, index = 7/11;  c_0 = 0.2727; c_1 = -0.005163;
            c_2 = 8.38e-05; c_3 = -5.831e-07; Ta = 21;
    end

    sunshineHours = index * maxSunHours;

        s = sunshineHours;
    B = 1.11*Ho*K^2;
    D = Ho*K - B;
    beta_0 = 15; z_0 = 3;
    initial_0 = [beta_0 z_0];
    [optimal, val_optimal] = fmincon(@myfunction_ex07,...

initial_0,[],[],[],[],lb,ub);

    % beta_optimal(n) = optimal;
    beta_optimal(n) = optimal(1); z_optimal(n) = optimal(2);
```

```
    year_gen(n,:) = generation;

    max_generation(n) = max(generation);

end
```

6. Optimization for no.5: myfunction_ex07

```
function g = myfunction_ex07(parameters)

beta_deg = parameters(1);
z = parameters(2);

global    omega_sunrise_i  omega_sunset_i  delta_deg  phi  omega_i
sinAlpha...
        B D generation c_0 c_1 c_2 c_3 Ta eps

for i = omega_sunrise_i : omega_sunset_i
    num  =  cosd(phi  -  beta_deg)*cosd(delta_deg)*cosd(omega_i(i)  -
z*sind(beta_deg)) + sind(delta_deg)*sind(phi - beta_deg);
    den           =           sind(delta_deg)*sind(phi)           +
cosd(delta_deg)*cosd(phi)*cosd(omega_i(i));
    rb(i) = num/den;
end

for i = 1:24
    if (i < 9) || (i > 19)
```

```
        rb(i) = 0;
    elseif (i < omega_sunrise_i) || (i >= omega_sunset_i)
        rb(i) = 0;
    end
end

invEff = 0.98;
capacityKWp = 2400000;
for i = 1:24
    rd = 0.5*(1 + cosd(beta_deg));
    generation(i) = invEff * capacityKWp * sinAlpha(i) *...
                    ((B * rb(i)) + (D * rd)) *...
                    (1 - (c_3 * beta_deg^3 + c_2 * beta_deg^2 + c_1 *
beta_deg + c_0)) *...
                    (1+ eps * (Ta - 25));
end

g = -sum(generation);
```

Appendix B: Public Survey and Questionnaire

Welcome to My Survey

I am Jubran, a PhD student at technology faculty, De Montfort University. As part of my research I am collecting data to assess the wastage of energy in Saudi homes. The main objectives are as follows:
1. to propose smart solutions to reduce the waste of electrical energy in homes;
2. to manage electrical demand from the consumer side;
3. to involve the citizen (consumer) solutions in energy conservation;

By answering a questionnaire you are agreeing to participate voluntarily.
Your name or any other personal identifying information will not appear in any publications resulting from this study.
The information gained from this questionnaire will only be used for the above objectives, will not be used for any other purpose and will not be recorded in excess of what is required for the research.
You may decide to withdraw from this study at any time by advising the researcher on email: p1401984x@myemail.dmu.ac.uk

1. What is your gender?

- Female
- Male

2. In what Region do you live?

- Central Region
- West Region
- East Region
- North Region
- South Region

* 3. What is the type of your accommodation?

- Villa
- Traditional house (one floor)
- Apartment
- Other (please specify)

4. How much amount of money in Saudi Riyals do you pay for electricity bill monthly?

100 - 300	301 - 500	501 - 700	701 - 900	More than 900
○	○	○	○	○

Other (please specify)

5. How many family members normally live in the accommodation?

- ○ more than 7
- ○ 7
- ○ 6
- ○ 5
- ○ 4
- ○ 3
- ○ 2

* 6. How many guest rooms are there in your house?
(Guest rooms = Men's living room + women's living room + dining room)

- ○ 1
- ○ 2
- ○ 3
- ○ 4 or more

Other (please specify)

7. How many bedrooms are there in your house?

- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ 6
- ○ 7
- ○ more than 7

* 8. How many bathrooms are there in your house?

- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ 7
- ◯ more than 7

* 9. How many heating water cylinders are there in your house?

- ◯ less than 3
- ◯ 3
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ 7
- ◯ More than 7

* 10. How many air conditioning units are there in your house?

- ◯ 3 or less
- ◯ 4
- ◯ 5
- ◯ 6
- ◯ 7
- ◯ 8
- ◯ 9
- ◯ 10
- ◯ more than 10

* 11. What kind of air conditioning units are there in your house?

- ◯ Window
- ◯ Split
- ◯ Combined of window and split
- ◯ Central

Other (please specify)

12. Which appliances have the highest electricity costs (consumption)?
(you can choose more than one answer)

- ☐ Air conditioning
- ☐ Wash machine
- ☐ Dish washer
- ☐ Water heater

13. How many days a week is the men's guest room occupied?

1 days	2 days	3 days	4 days	5 days or more
◯	◯	◯	◯	◯

Other (please specify)

14. On typical days, which intervals by hours is the men's guest room used?
(you can choose more than one answer)

- ☐ 8 am - 11 am
- ☐ 11 am - 3 pm
- ☐ 3 pm - 7 pm
- ☐ 7 pm - 11 pm
- ☐ After 11 pm
- ☐ Most of the time

Other (please specify)

15. How many days a week is the women's guest room occupied?

1 days	2 days	3 days	4 days	5 days or more	No women's guest room
○	○	○	○	○	○

Other (please specify)

16. On typical days, which intervals by hours is the women's guest room used? (you can choose more than one answer)

- [ ] 8 am - 11 am
- [ ] 11 am - 3 pm
- [ ] 3 pm - 7 pm
- [ ] 7 pm - 11 pm
- [ ] After 11 pm
- [ ] Most of the time

Other (please specify)

17. How many days a week is the dining room occupied?

1 days	2 days	3 days	4 days	5 days or more	No dining room
○	○	○	○	○	○

Other (please specify)

* 18. On typical days, which intervals by hours is the dining room occupied?
You can choose more than one answer

- [ ] 5 am - 8 am
- [ ] 8 am - 11 am
- [ ] 11 am - 3 pm
- [ ] 3 pm - 11 pm
- [ ] After 11 pm
- [ ] Most of the time
- [ ] No lounge

Other (please specify)

* 19. On typical days, which intervals by hours are bedrooms occupied?
You can choose more than one answer

- [ ] 5 am - 8 am
- [ ] 8 am - 11am
- [ ] 11 am - 3 pm
- [ ] 3 pm - 7 pm
- [ ] 7 pm - 11 pm
- [ ] After 7 pm (sleeping time)

Other (please specify)

* 20. How many bedroom are rarely occupied?
(or used as a store)

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] more than 3

Other (please specify)

* 21. On typical days, which intervals by hours is the lounge occupied?
You can choose more than one answer

- [ ] 5 am - 8 am
- [ ] 8 am - 11 am
- [ ] 11 am - 3 pm
- [ ] 3 pm - 11 pm
- [ ] After 11 pm
- [ ] Most of the time
- [ ] No lounge

Other (please specify)

* 22. At which temperature do you often adjust the air conditioning thermostat in summer?

- ○ Below 18°C
- ○ Between 18 - 20°C
- ○ Between 21 - 23°C
- ○ Between 23 - 25°C
- ○ more than 25 °C

Other (please specify)

* 23. How often do you remember to shut-down the Air-Conditioning (A/C) when you are leaving any room in your house?

always	usually	sometimes	rarely	never
○	○	○	○	○

24. How many heating water cylinders do you switch on in the summer?

- all
- 1
- 2
- 3
- 4 or more
- None
- Other (please specify)

* 25. To what extent do you agree to adopt technical solutions in your home to reduce wasted energy?

Strongly Disgree	Disagree	Neutral	Agree	Strongly Agree

Other (please specify)

* 26. To what extent do you agree to install an automatic A/C (air conditioning)- control system if it will reduce your bill?

Strongly Disgree	Disagree	Neutral	Agree	Strongly Agree

* 27. Do you know what the term "renewable energy" means?

- I do not know
- I hear about it but I do not know what does it mean
- I know a little bit
- Yes I know

* 28. To what extent do you agree with installation of solar cells on your house roof?

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

Other (please specify)

29. Do you want to add any comment or suggestion?

- ◯ No
- ◯ Yes

Appendix C: Simulation's Results

B1. House 1-Annually Simulation results of energy consumption at 20°C thermostat setting under continuous mode

Report: **Annual Building Utility Performance Summary**

For: **House 1 at 20°C**

Timestamp: **2018-01-26 15:43:35**

Values gathered over 8760.00 hours

Site and Source Energy

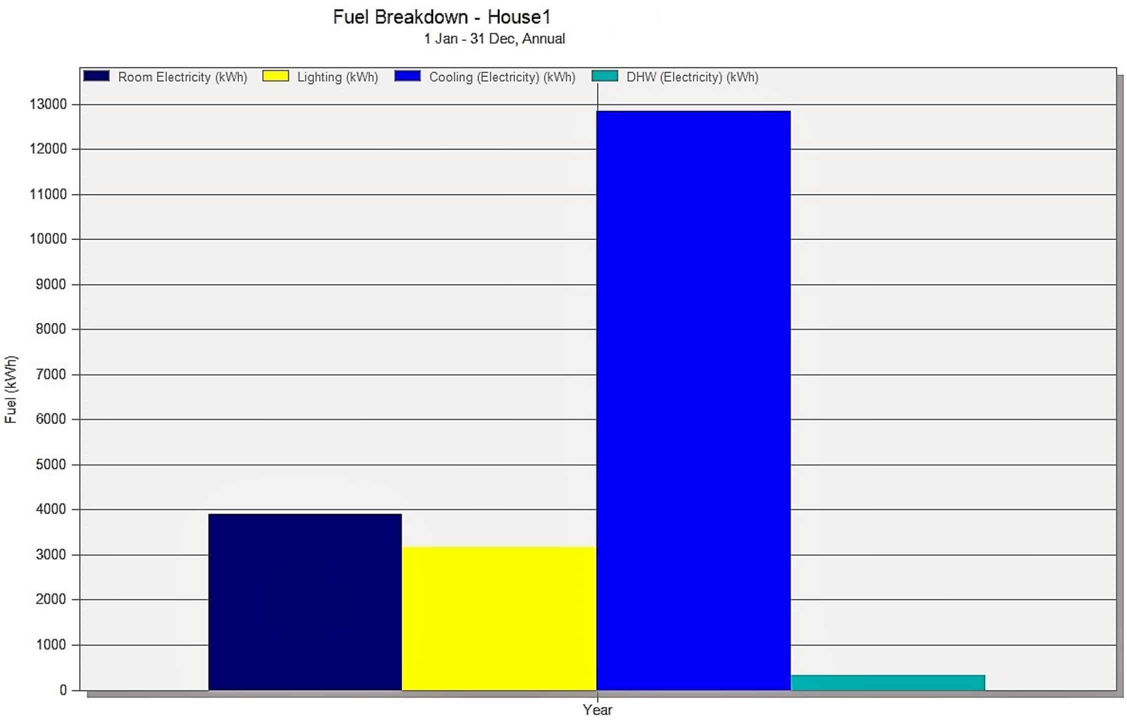
	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	32672.76	183.88	228.24
Net Site Energy	32672.76	183.88	228.24
Total Source Energy	53995.67	303.88	377.20
Net Source Energy	53995.67	303.88	377.20

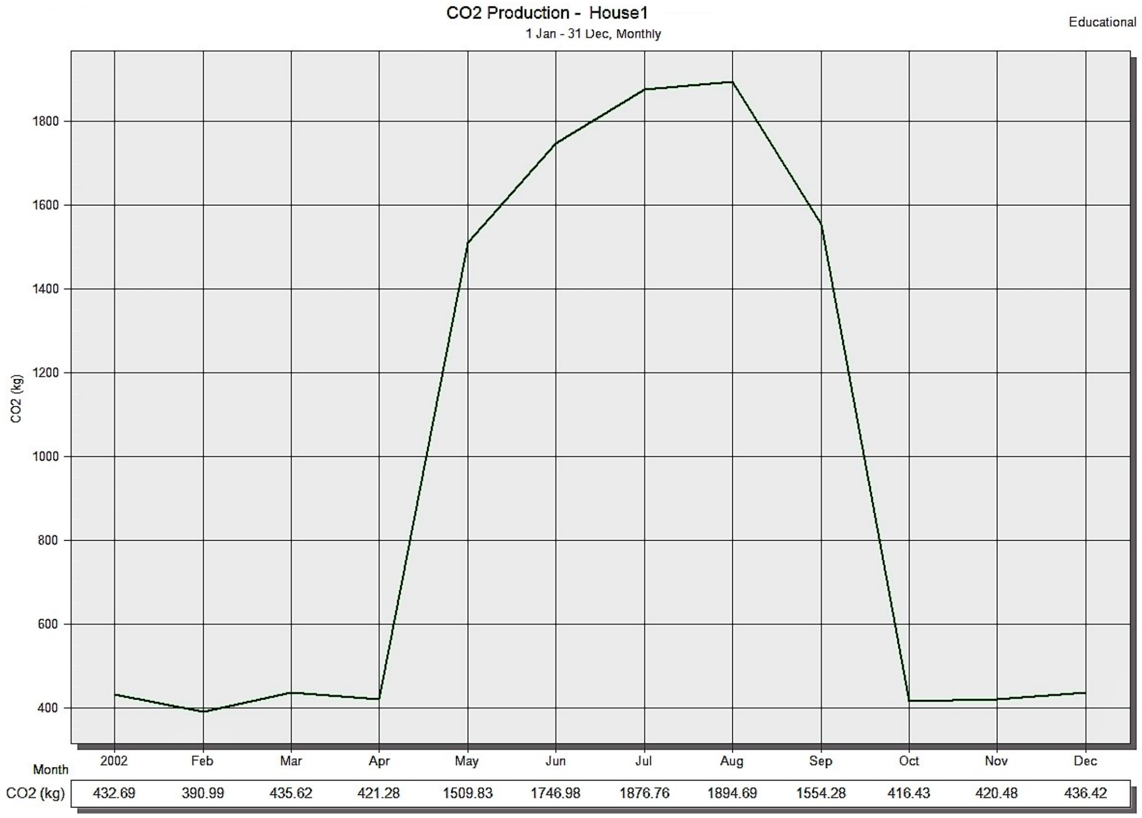
Building Area

	Area [m2]
Total Building Area	177.69
Net Conditioned Building Area	143.15
Unconditioned Building Area	34.54

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Interior Lighting	3534.95	0.00	0.00	0.00	0.00	0.00
Interior Equipment	4430.12	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	1050.64	16.45
Total End Uses	7965.08	0.00	0.00	23657.04	1050.64	16.45


Fuel Breakdown - House1
1 Jan - 31 Dec, Annual
Room Electricity (kWh)
Lighting (kWh)
Cooling (Electricity) (kWh)
DHW (Electricity) (kWh)
Fuel (kWh)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
Year


CO2 Production - House1
1 Jan - 31 Dec, Monthly
Educational
CO2 (kg)
400
600
800
1000
1200
1400
1600
1800
Month
2002
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
CO2 (kg)
432.69
390.99
435.62
421.28
1509.83
1746.98
1876.76
1894.69
1554.28
416.43
420.48
436.42

B2. House 1- Annually Simulation results of energy consumption at 24°C thermostat setting under continuous mode

Report: **Annual Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2018-01-26 17:56:20**

Values gathered over 8760.00 hours

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	23344.97	131.38	163.08
Net Site Energy	23344.97	131.38	163.08
Total Source Energy	44148.64	248.46	308.41
Net Source Energy	44148.64	248.46	308.41

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Cooling	0.00	0.00	0.00	14329.25	0.00	0.00
Interior Lighting	3534.95	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	1050.64	16.45
Total End Uses	7965.08	0.00	0.00	14329.25	1050.64	16.45

B3. House 1- Monthly Simulation results of energy consumption at 20°C thermostat setting under continuous mode

- **January**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	1132.81	6.38	7.91
Net Site Energy	1132.81	6.38	7.91
Total Source Energy	3645.04	20.51	25.46
Net Source Energy	3645.04	20.51	25.46

- **February**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	1022.84	5.76	7.15
Net Site Energy	1022.84	5.76	7.15
Total Source Energy	3291.21	18.52	22.99
Net Source Energy	3291.21	18.52	22.99

- **March**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	1142.46	6.43	7.98
Net Site Energy	1142.46	6.43	7.98
Total Source Energy	3675.63	20.69	25.68
Net Source Energy	3675.63	20.69	25.68

- **April**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	1106.69	6.23	7.73
Net Site Energy	1106.69	6.23	7.73
Total Source Energy	3560.48	20.04	24.87
Net Source Energy	3560.48	20.04	24.87

- **May**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	4658.06	26.21	32.54
Net Site Energy	4658.06	26.21	32.54
Total Source Energy	6464.87	36.38	45.16
Net Source Energy	6464.87	36.38	45.16

- **June**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	4590.45	25.83	32.07
Net Site Energy	4590.45	25.83	32.07
Total Source Energy	5624.55	31.65	39.29
Net Source Energy	5624.55	31.65	39.29

- **July**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	5028.27	28.30	35.13
Net Site Energy	5028.27	28.30	35.13
Total Source Energy	6117.01	34.43	42.73
Net Source Energy	6117.01	34.43	42.73

- **August**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	5046.06	28.40	35.25
Net Site Energy	5046.06	28.40	35.25
Total Source Energy	6135.79	34.53	42.86
Net Source Energy	6135.79	34.53	42.86

- **September**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	3757.22	21.15	26.25
Net Site Energy	3757.22	21.15	26.25
Total Source Energy	4744.93	26.70	33.15
Net Source Energy	4744.93	26.70	33.15

- **October**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	1046.61	5.89	7.31
Net Site Energy	1046.61	5.89	7.31
Total Source Energy	3337.10	18.78	23.31
Net Source Energy	3337.10	18.78	23.31

- **November**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	1100.54	6.19	7.69
Net Site Energy	1100.54	6.19	7.69
Total Source Energy	3541.00	19.93	24.74
Net Source Energy	3541.00	19.93	24.74

- **December**

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	1148.62	6.46	8.02
Net Site Energy	1148.62	6.46	8.02
Total Source Energy	3695.11	20.80	25.81
Net Source Energy	3695.11	20.80	25.81

B4. House 1-Annually Simulation results of energy consumption at 20°C thermostat setting under schedule mode (Mode 1)

Report: **Annual Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2018-01-26 14:38:52**

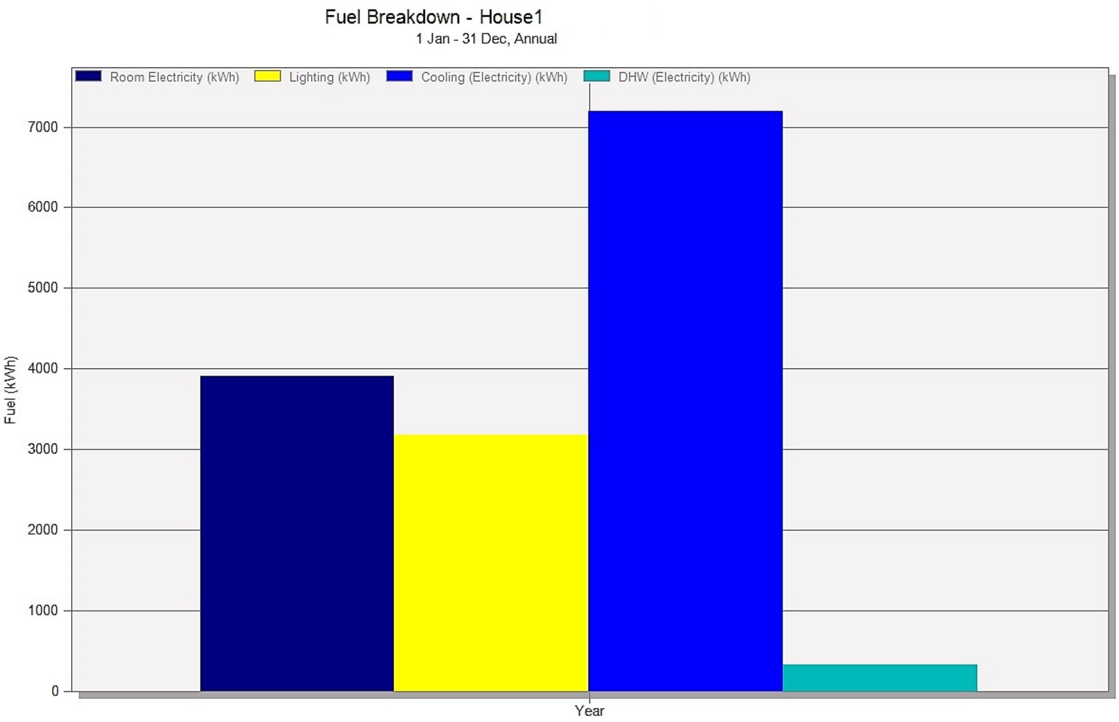
Values gathered over 8760.00 hours

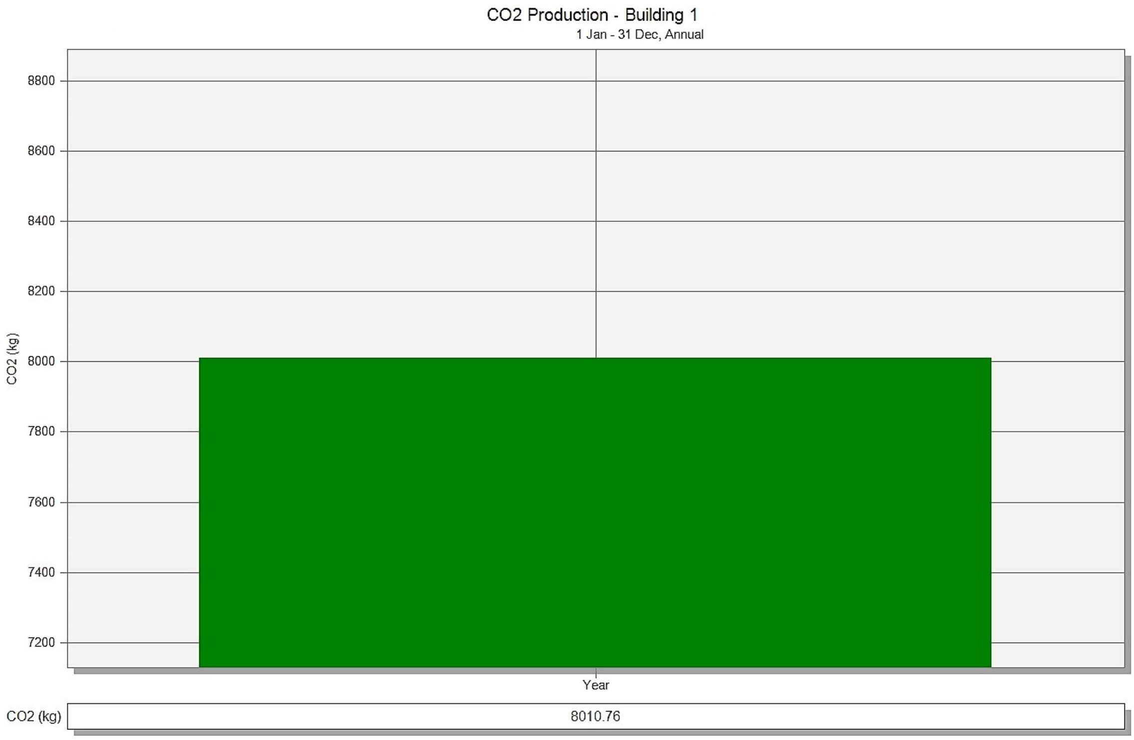
Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	22881.75	128.78	159.85
Net Site Energy	22881.75	128.78	159.85
Total Source Energy	43659.63	245.71	305.00
Net Source Energy	43659.63	245.71	305.00

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Interior Lighting	3534.95	0.00	0.00	0.00	0.00	0.00
Interior Equipment	4430.12	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	1050.64	16.45
Total End Uses	7965.08	0.00	0.00	13866.03	1050.64	16.45


Fuel Breakdown - House1
1 Jan - 31 Dec, Annual
Room Electricity (kWh)
Lighting (kWh)
Cooling (Electricity) (kWh)
DHW (Electricity) (kWh)
Fuel (kWh)
7000
6000
5000
4000
3000
2000
1000
0
Year


CO2 Production - Building 1
1 Jan - 31 Dec, Annual
CO2 (kg)
8800
8600
8400
8200
8000
7800
7600
7400
7200
Year
CO2 (kg)
8010.76

B5. House 1-Monthly simulation results of energy consumption at 20°C thermostat setting under schedule mode (Mode 1)

- **May**

Report: **Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2018-01-26 14:50:55**

Values gathered over 744.00 hours

WARNING: THE REPORT DOES NOT REPRESENT A FULL ANNUAL SIMULATION.

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	2921.86	16.44	20.41
Net Site Energy	2921.86	16.44	20.41
Total Source Energy	4632.02	26.07	32.36
Net Source Energy	4632.02	26.07	32.36

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Cooling	0.00	0.00	0.00	2199.57	0.00	0.00
Interior Lighting	300.23	0.00	0.00	0.00	0.00	0.00
Interior Equipment	371.66	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	50.41	0.79
Total End Uses	671.89	0.00	0.00	2199.57	50.41	0.79

- **June**

Report: **Annual Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2018-01-26 14:52:29**

Values gathered over 720.00 hours.

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	3422.55	19.26	23.91
Net Site Energy	3422.55	19.26	23.91
Total Source Energy	5129.50	28.87	35.83
Net Source Energy	5129.50	28.87	35.83

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Cooling	0.00	0.00	0.00	2714.63	0.00	0.00
Interior Lighting	290.54	0.00	0.00	0.00	0.00	0.00
Interior Equipment	368.60	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	48.78	0.76
Total End Uses	659.14	0.00	0.00	2714.63	48.78	0.76

- **July**

Report: **Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2018-01-26 14:54:24**

Values gathered over 744.00 hours

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	3660.99	20.60	25.57
Net Site Energy	3660.99	20.60	25.57
Total Source Energy	5412.29	30.46	37.81
Net Source Energy	5412.29	30.46	37.81

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Cooling	0.00	0.00	0.00	2938.69	0.00	0.00
Interior Lighting	300.23	0.00	0.00	0.00	0.00	0.00
Interior Equipment	371.66	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	50.41	0.79
Total End Uses	671.89	0.00	0.00	2938.69	50.41	0.79

- **August**

Report: **Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2018-01-26 14:55:16**

Values gathered over 744.00 hours

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	3695.95	20.80	25.82
Net Site Energy	3695.95	20.80	25.82
Total Source Energy	5459.40	30.72	38.14
Net Source Energy	5459.40	30.72	38.14

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Cooling	0.00	0.00	0.00	2968.83	0.00	0.00
Interior Lighting	300.23	0.00	0.00	0.00	0.00	0.00
Interior Equipment	376.49	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	50.41	0.79
Total End Uses	676.72	0.00	0.00	2968.83	50.41	0.79

- **September**

Report: **Annual Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2018-01-26 14:56:07**

Values gathered over 720.00 hours

Site and Source Energy

	Total Energy [kWh]	Energy Per Total Building Area [kWh/m2]	Energy Per Conditioned Building Area [kWh/m2]
Total Site Energy	3028.14	17.04	21.15
Net Site Energy	3028.14	17.04	21.15
Total Source Energy	4702.94	26.47	32.85
Net Source Energy	4702.94	26.47	32.85

End Uses

	Electricity [kWh]	Natural Gas [kWh]	Additional Fuel [kWh]	District Cooling [kWh]	District Heating [kWh]	Water [m3]
Heating	0.00	0.00	0.00	0.00	0.00	0.00
Cooling	0.00	0.00	0.00	2325.05	0.00	0.00
Interior Lighting	290.54	0.00	0.00	0.00	0.00	0.00
Interior Equipment	363.77	0.00	0.00	0.00	0.00	0.00
Water Systems	0.00	0.00	0.00	0.00	48.78	0.76
Total End Uses	654.31	0.00	0.00	2325.05	48.78	0.76